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EDITORIAL

Journal of Energy special issue: Papers from 47. CIGRÉ Session held on 24th August 2020 to 3rd September 2020 in Paris/France.

Paris CIGRÉ Session is the world's number one global power system event. This event attracts members from across the whole CIGRE community and is the culmination of the previous two years of the CIGRÉ knowledge program. The Paris Session is unlike any other conference. It offers an in-depth interactive congress, following a rigorous process where, rather than being presented, hundreds of papers are collaboratively debated.

As Philippe Adam, General Secretary of CIGRÉ noticed, for the second time in CIGRÉ history, the governing bodies of the Association have decided not to hold this flagship Paris event as initially planned. The first time this happened was when World War II had set the world ablaze. This time, the high risks created by the Covid-19 pandemic lead to this decision. The evolution of the disease and its consequences on world economics did not preserve any region of the world, and the results showed this was the good decision. The first CIGRÉ e-session was a great success. More than 2500 virtual delegates attended at least one of the 83 sessions, versus an initial estimate of 1000. The opening session was followed by 800 attendees, and we measured an average of 1500 daily connections from August 24th to September 3rd. Even the recorded sessions were an unexpected success with more than 5000 views by the end of September.

At the Paris Session, Authors papers are circulated to delegates and carefully analyzed in advance by the Study Committee 'Special Reporters'. Before the Paris Session, these Special Reporters prepare a series of questions addressed to the community in order to stimulate contributions. The 'Group Discussion Meeting' of each Study Committee, managed by the Special Reporter, allows the selected 'Contributors' to present their point of view and experience, before an audience of experts. This way the collective expertise of the Contributors is harnessed to create new ideas that build on what the author presented in their paper under discussion.

In this special issue, 6 papers were accepted for publication in Journal of Energy after additional peer-review process. The papers are from different Study committees as follows:

SC-A1: Static eccentricity fault detection method for electrical rotating machines based on the magnetic field analysis in the air gap by measuring coils

SC-A2: Fleet Asset Management Opportunities Arising from Transient Monitoring of Power Transformers and Shunt Reactors

SC-B3: Contractors as modern Master Builders: Virtual Design and Construction as an enabler of meaningful experiences to project teams for achieving optimized substation management

SC-C1: Multicriterial analyses and selection of the best option for revitalization and development of the southern part of Croatian 400 kV network and connection to the power system of Bosnia and Herzegovina

SC-C2: Advanced and Rapid Tool in Control Room to Determine the Cause and Location of Events in Transmission Network

SC-C5: Development and Impact of Flow-Based Methodology in Core Region

Authors of these papers are mostly members of the Croatian National Committee CIGRÉ, so this special edition gives in some way a current review of the projects and issues in the Croatian power system, Industry and Science community.

Goran Slipac
Editor-in-Chief

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Static eccentricity fault detection method for electrical rotating machines based on the magnetic field analysis in the air gap by measuring coils

SUMMARY

Electrical rotating machines have a great economic significance as they enable conversion of energy between mechanical and electrical state. Reliability and operation safety of these machines can be greatly improved by implementation of continuous condition monitoring and supervisory systems. Especially important feature of such systems is the ability of early fault detection. For this reason, several methods for detection and diagnosis of the machine faults have been developed and designed. As fault detection methods can largely differ in the types of detectable faults, machine adoptability and price of the system, a novel method was developed that can be used for cost-effective detection of various faults of electrical machine. Machine fault detection technique presented in this paper is based on the measurement of magnetic field in the air gap. Numerous studies have proven that crucial information about the machine condition can be determined based on measurement and analysis of the magnetic field in the air gap. It has also been confirmed that analysis of the air gap magnetic field can be used to detect, diagnose and recognize various electrical faults in their very early stage. Proposed method of positioning and installation of the measuring coils on ferromagnetic core parts within the air gap region of the machine enables differentiation of various faults. Furthermore, different faults can be detected if measuring coils are placed on the stator teeth then when placed on the rotor side. The paper presents method on how to analyse and process the measured voltages acquired from measuring coils placed within the machine, especially in the case of rotor static eccentricity detection. The methodology is explained by means of finite element method (FEM) calculations and verified by measurements that were performed on the induction machine. FEM calculation model was used to predict measurement coil output of the induction motor for healthy and various faulty states (at different amounts of static eccentricity). These results were then confirmed by measurements performed in the laboratory on the induction traction motor that was specially modified to enable measurements of faulty operation states of the machine. Measurements comprised of several machine fault conditions broken one rotor bar, broken multiple rotor bars, broken rotor end ring and various levels of rotor static eccentricity.

Other methods used for faults detection are primarily based on the monitoring of quantities such as current and vibration and their harmonic analysis. This new system is based on the tracing the changes of induced voltage of the measuring coils installed on the stator teeth. Faults can be detected and differentiated based on RMS value of these voltages and the number of voltage spikes of voltage waveform i.e. without the need of harmonic analyses. If these coils are installed on the rotor it is possible to detect the stator winding faults in a similar manner.

KEYWORDS

static eccentricity, induction machine, squirrel-cage rotor, finite element, magnetic field, air gap, measuring coil, faults detection

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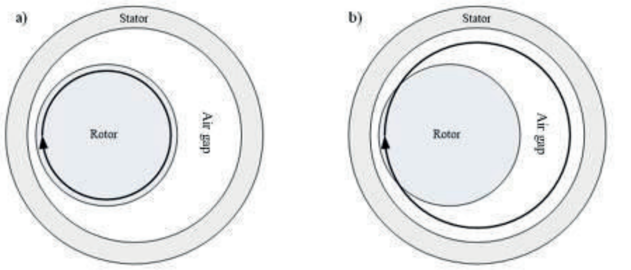
NTRODUCTION

Induction motors are one of the most common types of electrical rotating machines. These machines play an important role independently or as part of a complex process, and are widely present in the power plants, oil refineries, chemical plants, metal foundries, pumping stations, coal mills, paper industry, etc. Because of the importance in the process, it is necessary to prevent failures and ensure reliability and availability of key induction motors. To achieve these tasks all key machines, contain some types of protection, supervision, and monitoring. Also, one of the main goals is early and reliable fault detection and provision of mutual recognition of each fault. Majority of induction motor faults is caused by electrical and mechanical conditions of the machine combined with operational environment. According to the literature [1 – 4], the most common faults of induction machines are bearing faults, following stator and rotor faults and other faults such as different types of eccentricity (static, dynamic or both). In order to early detect and recognize induction machine fault, various types of fault detection methods have been developed [5, 6, 7, 8]. These methods are a result of long-term testing, measurement, and monitoring of the induction machine operation. All these methods with more or less success enable fault detection of induction motor.

One of the common motor problems is the occurrence of rotor static eccentricity that exceeds the allowable limit [9]. There are generally two kinds of rotor eccentricities: static or dynamic (showed on the figure 1). In the case of static eccentricity, the rotor turns around its centre of gravity, but this centre is displaced of the stator centre line. From the stator point of view, the place of minimal air gap occurs at unchanged circular position. In the dynamic eccentricity case, the central axis of the rotor is not fixed but during rotation changes its position relative to the stator centre line. In this case the position of minimal airgap does not stay at the same stator circular position, but rather changes in time. Within this paper only the phenomenon of static eccentricity was analysed. The occurrence of rotor static eccentricity in induction machine can cause some of the following undesirable effects: vibrations, unbalanced magnetic pull (UMP), additional losses in the rotor winding and in parallel circuits of the stator windings, occurrence of the shaft voltages and currents, additional losses in the stator or rotor core, and finally in the worst case scenario physical contact of the rotor with the stator [10]. These undesirable effects either reduce the machine performance and efficiency or make secure operation of the machine impossible and therefore lead to the complete machine shutdown.

Figure 1. Types of eccentricities: a) static b) dynamic



In order to early detect and recognize static eccentricity problem, various types of fault detection methods have been developed [11, 12, 13, 14]. This paper presents new methodology for static eccentricity detection that was developed as part of the continuous research in the field of rotating machine fault detection techniques. The basis for this new innovative methodology can be find in the previous research that was presented within the paper [15]. Within the previous research the squirrel-cage faults (such as broken bar/s or ring) and the possibility of their early fault detection were analysed.

The new approach for rotor static eccentricity detection described in this paper is based on the air-gap magnetic field analysis. Presented methodology is more reliable and requires less data processing than other known methods. The magnetic field is determined by measuring coils embedded in the machine airgap, installed on the stator teeth, and mutually spaced for the pole pitch. Based on the voltage waveforms and RMS values of the induced voltages in the measuring coils it is possible to detect rotor eccentricity of the induction machine. In the paper results obtained by finite element method (FEM) and measurement on the real induction motor are presented. In order to show changes in the induced voltage waveforms and RMS voltage values of the measuring coils, numerical simulations on the FEM model have been performed. At first, FEM calculation for a regular motor operation was conducted. Then, using the same FEM model with modifications in placement of the machine rotor centre point position the cases of static eccentricity were simulated. In the FEM model, the rotor of the motor was shifted in the direction of ±y axes for achieving differences in static eccentricity. To detect the existence of static eccentricity, induced voltages in measuring coils mutually spaced for the pole pitch were observed and analysed. Based on the RMS value change of the induced voltage in the coils, the presence of rotor displacement and static eccentricity was determined. FEM result were verified through measurements on the induction machine.

The aim of the paper is a contribution to early and reliable rotor eccentricity detection of induction machines, based on the magnetic field analysis in the air gap. The novelty of this new methodology is magnetic field analysis obtained by measuring coils installed in the airgap of induction machine. The main advantage of this methodology is that it avoids complex signal processing and the need for harmonic analysis of the measured signal. The presence of rotor static eccentricity is determined by detection of changes in induced voltage waveform and RMS value in the measuring coils, mutually spaced for a pole pitch.

FEM ANALYSIS OF THE INDUCTION MACHINE

The FEM analysis was performed in the commercial software *Infolytica Magnet*. Two-dimensional FEM model of the squirrel-cage induction motor is showed on the figure 2.a). The figure 2.b) shows distribution of the magnetic field together with the position of the measuring coils. These measuring coils are in the airgap, installed on the stator teeth and circularly spaced for a pole pitch, $_p$. To achieve reliable static eccentricity detection, it is necessary to ensure exactly this kind of measuring coils layout. Based on the waveform and RMS value of the induced voltage in the measuring coils it is possible to detect rotor eccentricity of the induction machine. To determine changes of these voltage values, numerical simulations on the FEM model have been performed. Table 1 lists regular and simulated faulty conditions of the analysed induction motor. Percentage of eccentricity is given in relation to the minimal air gap width. First, FEM calculation for a regular machine operation was performed. Then, using the same model with corresponding modifications the simulations of static eccentricity were performed. In the FEM model, the machine rotor was shifted in the direction of ±y axes for achieving changes of static eccentricity. The influence on the induced voltage in measuring coils circularly spaced for a pole pitch was observed and analysed with aim to detect the static eccentricity presence. Based on the RMS value change of the induced voltage in the coils, the presence of rotor displacement and static eccentricity is determined.

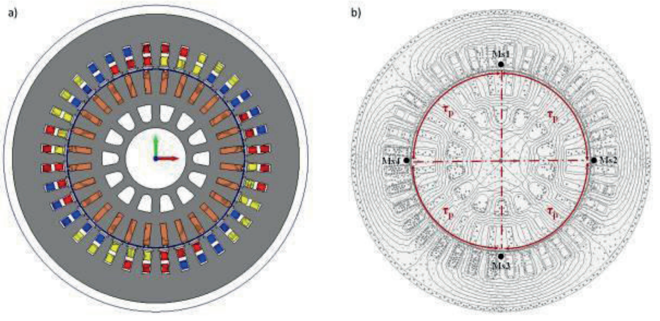


Figure 2. a) 2D FEM model; b) distribution of the magnetic field with position of the measuring coils

Table 1. Calculated regular and faulty conditions of the induction machine

Operating state	Regular condition	Faulty condition – static eccentricity	Model variant
Induction machine rated load	●		-
		●	15 % of static eccentricity
		●	20 % of static eccentricity
		●	25 % of static eccentricity

The figure 3.a) shows the voltage waveform induced in the measuring coils mutually spaced for the pole pitch, $_p$ obtained for regular operation condition. For correct voltage waveform interpretation, it is necessary to have certain information regarding machine active part elements and understand their impact on the measuring coil voltage waveform. Figure 3.b) presents the impact of the squirrel-cage rotor bars on the induced voltage waveform in the measuring coils. Numbers on this figure mark the impact of every rotor bar on the waveform. In one rotor turn, the waveform contains the number of rises and drops of the voltage that is exactly equal to the number of rotor bars. In the analysed case the induction machine has 28 rotor bars.

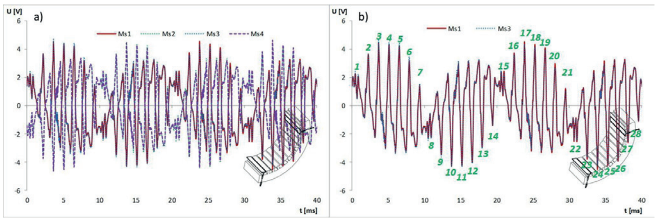


Figure 3. a) Induced voltage waveform in the measuring coils Ms1, Ms2, Ms3 and Ms4 – normal condition; b) impact of the squirrel-cage rotor bars on the induced voltage waveform

Following the regular machine operation, FEM simulations of static eccentricity listed in the table 1 were performed. Figure 4 shows induced voltage waveform in the measuring coils when rotor is displaced for 25 % of the air gap width in the – y axis direction. Figure 4.a) shows comparison of the induced voltage in the measuring coils Ms1 and Ms3, and figure 4.b) comparison of the voltage in the measuring coils Ms2 and Ms4. Through observation of these figures it can be noticed that the absolute value of voltage induced in the coil Ms3 is greater than the voltage induced in the coil Ms1. This result is expected, as the chosen rotor displacement direction places squirrel-cage rotor nearest to the coil Ms3, and farthest apart from the coil Ms1. The comparison of the induced voltage in the measuring coils Ms2 and Ms4 is shown on the figure 4.b). From this figure it can be concluded that the induced voltage in the mentioned measuring coils are equal. This result is expected as, in case of the chosen rotor displacement direction, the relative position of the rotor to these two coils stays the same.

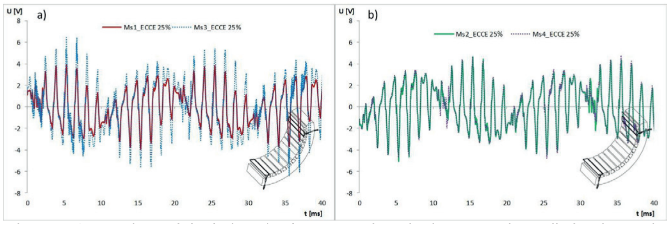


Figure 4. Comparison of the induced voltage waveform in the measuring coils for the static eccentricity amount 25% of the air gap (a shift in the – y axis): a) Ms1 and Ms3 diametrically spaced; b) Ms2 and Ms4 diametrically spaced

RMS values of the induced voltages in the measuring coils Ms1, Ms2, Ms3 and Ms4 obtained by FEM calculations due to the vertical rotor displacement are listed in table 2. These results lead to the following conclusions: when a static eccentricity occurs, induced voltage reaches the highest value in the coil that is nearest to the rotor, and the lowest in the coil that is farthest to the rotor; when the rotor is shifted in + y direction, the highest voltage is induced in the measuring coil Ms1 and the lowest in Ms3; when the rotor is shifted in – y direction, the highest voltage is induced in the measuring coil Ms3 and the lowest in Ms1; induced voltage value changes depending on the static eccentricity amount; the induced voltage values in the measuring coils Ms2 and Ms4 practically stayed unchanged with rotor displacement (positions perpendicular to the displacement direction, where the air gap size stays the same). In the case of the normal condition (without the presence of static eccentricity) the induced voltage values and the waveforms of the four measuring coils are symmetrical. The rotor displacement leads to differences in induced voltage waveforms and the RMS voltage values of the measuring coils. The last column in the table 2 shows the percentage deviation between the measuring coils with the highest voltage change due to the rotor displacement in the vertical direction. Based on the data in the table 2 the dependency curves between the induced voltage in the measuring coils and the rotor displacement in the vertical direction were determined. The figure 5.a) shows changes of the induced voltage RMS values in the measuring coils Ms1 and Ms3 and the figure 5.b) changes of the induced voltage RMS values in the measuring coils Ms2 and Ms4, due to rotor displacement in the vertical direction for different amounts of static eccentricity.

Table 2. RMS values of the induced voltage in the measuring coils obtained by FEM calculations due to the rotor displacement in a vertical direction

Δ [mm]	Motion direction	MS1 [V]	MS2 [V]	MS3 [V]	MS4 [V]	$\Delta U_{MS1/MS3}$[%]
– 0,25	to – y	2,155	2,468	3,011	2,533	39,72
– 0,20	to – y	2,213	2,475	2,894	2,520	30,74
– 0,15	to – y	2,283	2,484	2,777	2,522	21,66
0,00	centre	2,422	2,422	2,421	2,424	0,00
0,15	to + y	2,764	2,505	2,265	2,468	22,06
0,20	to + y	2,901	2,525	2,221	2,483	30,58
0,25	to + y	3,012	2,535	2,159	2,472	39,52

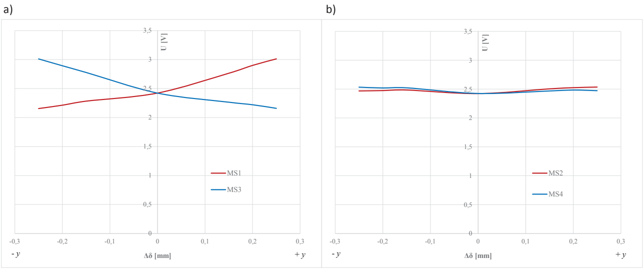


Figure 5. Changes of the induced voltage RMS values in the measuring coils due to rotor displacement in the vertical direction for different amounts of static eccentricity: a) measuring coils Ms1 and Ms3; b) measuring coils Ms2 and Ms4

MEASUREMENTS ON THE INDUCTION MACHINE

The measurements were performed on the squirrel-cage induction machine. The figure 6.a) shows analysed induction machine main parts. This motor was specially modified in order to analyse static eccentricity effects in the laboratory conditions. The eccentricity level control was possible due to the redesign of motor bearing shields, shown on the figure 6.b). The shown mechanism allows the change of rotor static eccentricity position through tightening of the positioning bolts. Figure 7.a) shows the positions of measuring coil installation on the stator teeth of the machine. The position and layout of the measuring coils installed in the tested motor is showed on the figure 7.b). The results obtained by measurements for regular condition are shown on the figure 8. The figure 8.a) shows the induced voltage waveform of the measuring coils Ms1, Ms2, Ms3 and Ms4, and the figure 8.b) the voltage induced in the coils Ms5, Ms6, Ms7 and Ms8.

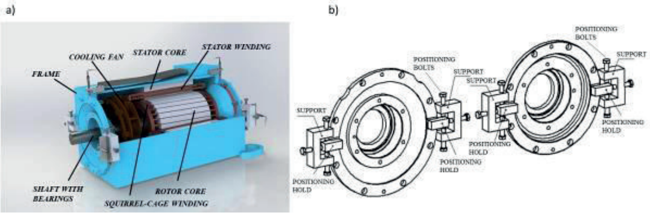


Figure 6. a) Squirrel-cage induction machine analysed in the laboratory; b) bearing shields adapted for static eccentricity simulation on the machine tested in the laboratory

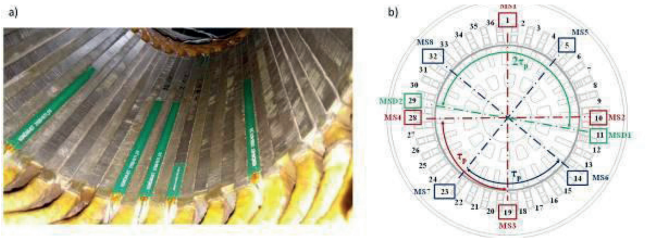


Figure 7. a) Measuring coil installation on the stator teeth of squirrel-cage induction machine; b) position of the measuring coils in the induction machine adapted for laboratory testing

Figure 9 shows results obtained by measurement for the case of 25 % of static eccentricity and the rotor displacement in the – y axis. On the figure 9.a) the voltage waveforms of the measuring coils Ms1 and Ms3 are showed, and on the figure 9.b) induced voltage in the measuring coils Ms2 and Ms4. The result obtained by the measurement are in accordance with the previously shown results obtained by FEM calculations for the same eccentricity level. The RMS values of the induced voltage in the measuring coils obtained by measurements due to the rotor displacement in a vertical direction are shown in the table 3. Based on these values, dependency curves between the induced voltages of the measuring coils and the rotor displacement in the vertical direction are derived. These curves are shown on the figures 10.a), 10.b) and 11. Due to the rotor displacement direction the biggest changes of the induced voltage RMS values are noticed in the measuring coils Ms1 and Ms3, as shown by the figure 10.a). Voltage changes of the coils Ms5, Ms6, Ms7 and Ms8 are also significant (figure 10.b), while voltages of measuring coils Ms2 and Ms4 had no noticeable change of RMS value (figure 11). The results obtained by the measurement are in the good alignment with the theses explained in the section with FEM results. The figure 12 shows comparison of the induced voltage in the measuring coil Ms1 obtained by FEM calculation and measurement for the case of the 25% of static eccentricity. In the case of voltage waveforms, the results are in good alignment, but some misalignment exist in the voltage amplitudes. This misalignment is the result of imperfections in coils installation, tolerances in machine design and deviations in the measurement process.

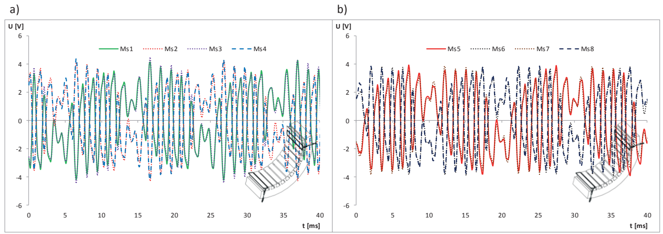


Figure 8. Measured results for the regular condition: a) induced voltage waveform in the measuring coils Ms1, Ms2, Ms3 and Ms4; b) induced voltage waveform in the measuring coils Ms5, Ms6, Ms7 and Ms8

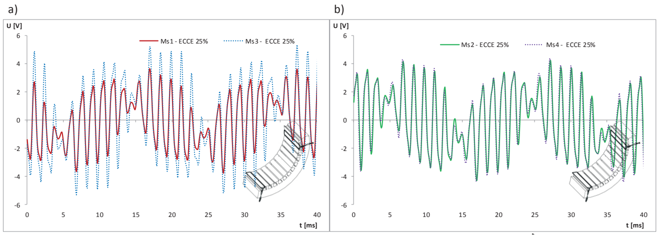


Figure 9. Measured results for the case of the 25% of static eccentricity: a) induced voltage waveform in the measuring coils Ms1 and Ms3; b) induced voltage waveform in the measuring coils Ms2 and Ms4

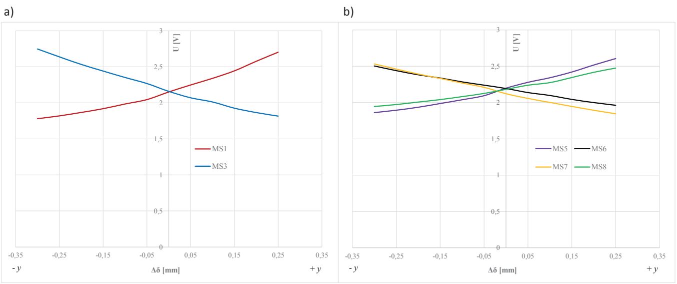


Figure 10. Changes of the induced voltage RMS values in the measuring coils due to rotor displacement in the vertical direction for different amounts of static eccentricity: a) measuring coils Ms1 and Ms3; b) measuring coils Ms5, Ms6, Ms7 and Ms8

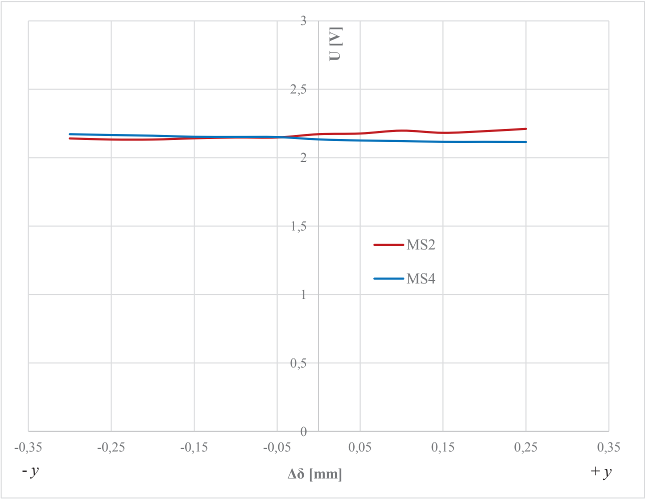


Figure 11. Changes of the induced voltage RMS values in the measuring coils due to rotor displacement in the vertical direction for different amounts of static eccentricity: measuring coils Ms2 and Ms4

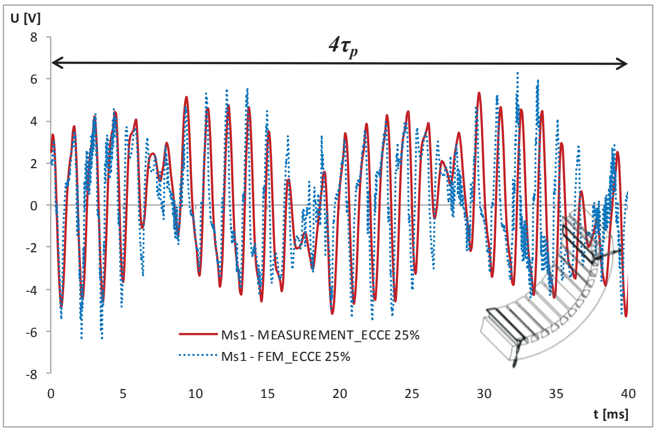


Figure 12. Comparison of the voltage induced in the measuring coil Ms1 obtained by FEM calculation and measurement for the case of the 25% of static eccentricity

Table 3. RMS values of the induced voltage in the measuring coils obtained by measurements

Δ[mm]	Motion direction	MS1 [V]	MS2 [V]	MS3 [V]	MS4 [V]	MS5 [V]	MS6 [V]	MS7 [V]	MS8 [V]	MSD1 [V]	MSD2 [V]	$\Delta U_{MS1/MS3}$[%]
-0,30	to – y	1,780	2,141	2,747	2,172	1,862	2,504	2,532	1,946	2,109	2,250	54,32
-0,25	to – y	1,819	2,133	2,638	2,166	1,895	2,44	2,461	1,973	2,116	2,234	45,02
-0,20	to – y	1,867	2,133	2,533	2,161	1,936	2,383	2,393	2,007	2,132	2,220	35,67
-0,15	to – y	1,919	2,142	2,441	2,153	1,987	2,338	2,333	2,041	2,152	2,201	27,20
-0,10	to – y	1,984	2,148	2,352	2,152	2,039	2,285	2,269	2,082	2,175	2,190	18,54
-0,05	to – y	2,045	2,148	2,268	2,151	2,095	2,240	2,210	2,126	2,181	2,170	10,90
0,00	centre	2,151	2,172	2,159	2,134	2,198	2,194	2,122	2,182	2,218	2,136	0,37
0,05	to + y	2,248	2,177	2,070	2,126	2,279	2,138	2,057	2,239	2,242	2,122	8,59
0,10	to + y	2,34	2,198	2,012	2,122	2,342	2,098	2,002	2,275	2,274	2,100	16,30
0,15	to + y	2,444	2,182	1,926	2,116	2,421	2,044	1,947	2,345	2,278	2,084	26,89
0,20	to + y	2,577	2,194	1,865	2,116	2,517	2,000	1,894	2,417	2,292	2,062	38,17
0,25	to + y	2,703	2,211	1,816	2,115	2,606	1,963	1,846	2,475	2,318	2,046	48,84

CONCLUSION

The aim of this paper is a contribution to the early and reliable rotor static eccentricity detection of squirrel-cage induction machines, based on the magnetic field analysis in the air gap. The new and innovative approach for rotor static eccentricity is presented. This is patent pending solution and intellectual property of KONCAR Electrical Engineering Institute. The novelty of this new methodology is magnetic field analysis obtained by measuring coils installed in the airgap of induction machine, and spatially spaced for pole pitch, $_p$. By FEM calculations and measurements, it is proven that by using the measuring coils on the stator teeth it is possible to detect static eccentricity occurrence in a very early stage (practically at 10% of static eccentricity appearance). One of the main advantages of this methodology is that it avoids complex signal processing and the need for harmonic analysis of the measured signals. Determination of rotor static eccentricity is based on the changes in induced voltage waveform and RMS value of the measuring coil voltage, i.e. in the distortion of the symmetry between the induced voltage in measuring coils.

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Fleet Asset Management Opportunities Arising from Transient Monitoring of Power Transformers and Shunt Reactors

SUMMARY

Power transformers and shunt reactors are strategic assets for every system operator and their downtime should be kept as low and controlled as possible. During their multi-decade service life, they are regularly exposed to transient overvoltages. These situations stress their insulation systems and can cause accelerated deterioration and aging. Since the shapes of these overvoltages are usually unknown, an additional approach to assessing the health index can be realized using monitoring systems with transient recorders. Analyzing the transient overvoltages using frequency domain severity factor, a quantification of additional stress on the transformer's/shunt reactor's insulation can be given. This can help in assessing the current state of the insulation system and can lead to more advanced fleet asset management.

KEYWORDS

transformer transient monitoring system, overvoltage stress, frequency domain severity factor, health index estimation, fleet asset management

INTRODUCTION

Power transformers and shunt reactors are subjected to various dielectric stresses during their service life [1]. These stresses are always caused by external factors such as switching operations or atmospheric discharges. Such repeatable stresses cause insulation degradation of the high voltage equipment which can consequently lead to their failure [2]. Since power transformers and shunt reactors are strategic assets in transmission and distribution network, their unplanned downtime can cause substantial financial loss. Therefore, it is necessary to monitor these transient events within a transmission system and possibly assess their long-term impact on installed strategic equipment.

As the transients that occur in the power network differ from the standardized test impulses, monitoring systems can be used to broaden the knowledge about the waveshapes and amplitudes of the overvoltages that can occur in the network and stress the units in the grid. This is in line with the current discussions within the CIGRE about the nonstandard waveshapes for the impulse testing. High frequency transformer models can help in evaluating the impact of nonstandard impulse waveshapes on the transformer or reactor insulation, especially in the case of the units already installed in the power network.

In this paper, a brief overview of the existing transformer transient monitoring systems is given first. Then a validation of the transient monitoring system with the measurements done in the high voltage laboratory for various voltage levels and shapes is shown. Finally, the possibilities of transient monitoring system in transformer fleet asset management is addressed using the Frequency Domain Severity Factor (FDSF).

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TRANSFORMER TRANSIENT MONITORING SYSTEM

Monitoring systems are installed across numerous locations around the globe. All modern-day systems should have, apart from the measured quantities, the algorithms for parameter estimation and trend comparison of current values with the predictive models. Monitoring the transformer transients is currently the state of the art of advanced transformer monitoring systems.

Extensive experience of continuous monitoring of transients in the power system shows that the measured data can be correlated with the lightning location system data and to the SCADA events [3]. Moreover, the data collected from the transformer fleet can be used to assess the real conditions in the power network and to help in deciding the equipment parameters and coordinating the insulation level for the future power transformers and reactors that will be installed at the same or similarly stressed nodes in the network. It is possible to take into account the observed transients when assessing the health index of the transformer which has an impact on network reliability. This can, in turn, lead to technically successful and economically sound fleet asset management.

A common approach is to measure voltage transients across the bushing measuring taps of power transformers or reactors [4]. A special bushing tap adapter and measuring impedance need to be designed in order to accurately transfer the overvoltage amplitude and shape to the low voltage side. This needs to be valid for the whole frequency range of interest, which is usually up to 1 MHz for the air insulated substations. Currently, several commercially available transformer monitoring systems that are capable of measuring and recording transient activities exist. In this paper, Končar TMS+ system was used. The most recent versions of such system can record transients at up to 16 channels with the sample rate of 4.5 MS/s and recordings up to 7 seconds long.

PERFORMANCE CHECK OF TRANSIENT MONITORING SYSTEM

In this chapter a verification of the transient monitoring system has been described. The verification has been done both in frequency and in time domain. Furthermore, the real case overvoltage examples from the real power network are presented.

Verification of System in High Voltage Laboratory

In order to be certain that the high-to-low voltage bridge does not influence the measured overvoltage signals, the frequency response of the measurement circuit needs to be checked. This was done using the vector network analyser Omicron Bode 100. The voltage ratio between the high voltage bushing connection and the bushing test tap needs to be as linear as possible for the frequencies of interest.

The object under test was Končar OTF 1050/245 kV bushing with C_1=326 pF and C_2=362 pF. The measurement configuration (bushing, bushing test tap, connection of coaxial cables to the top of the bushing, measuring impedance of TMS+ system connected to the test tap) and the measured results are shown in Figures 1 and 2, respectively. As expected, the frequency response of the test circuit remained stable until 1 MHz.

Figure 1: Electrical circuit configuration for frequency response check of the Končar TMS+ measuring system.

Once the validation of the measuring device has been done in the frequency domain, it is necessary to validate the whole transient monitoring system on the real transformer or shunt reactor. For the purpose of this paper, a 100 MVAr 220 kV variable shunt reactor (VSR) is used as a test object. Insulation level of the reactor is SI 750 kV, LI 950 kV, LIC 1045 kV, AC 395 kV, U_m 245 kV.

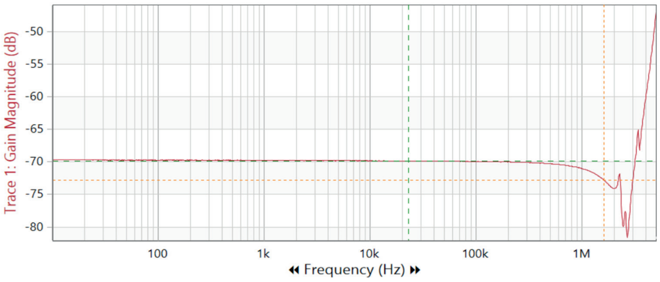


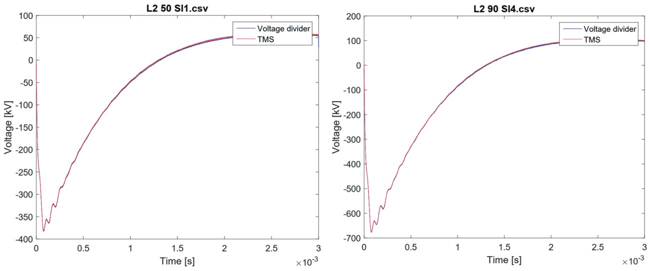
Figure 2: Frequency response of the Končar TMS+ measuring system.

During the lighting impulse test of the shunt reactor, the voltages are observed in parallel using the transient monitoring system in addition to measurements done using the voltage divider as is normally done in the high voltage laboratory during the impulse testing. The test sequence consisted of several different switching, lightning and chopped impulses (SI, LI and LIC) with different voltage amplitudes [5], [6]. In continuation, the comparison between signals measured using voltage divider and the transient monitoring system is shown.

(a) (b)

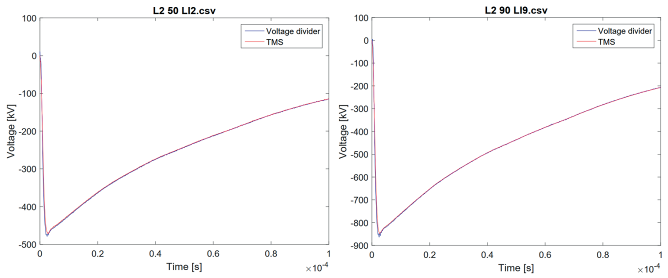
Figure 3: TMS+ system (a) installed in a 100 MVAr 220 kV VSR (b).

From Figures 4-6, it can be seen that the transient monitoring system accurately measures the standard test impulses, with the exception of the fast oscillations after chopping during LIC. This is expected since the inductances in the measuring circuit of the monitoring system are limiting the change rate of the signal thus causing the slight error at higher frequencies. It is important to note that all the impulses are observed on the same reactor phase L2 and the multiplier remained constant throughout the test. This means that all the events captured with the transient recorder are linear with voltage showing its applicability not only for a wide frequency range but for a wide overvoltage amplitude range as well.



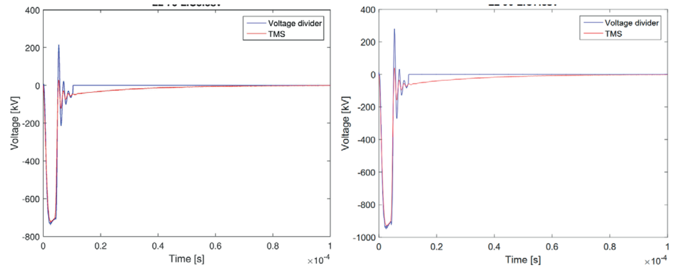
(a) (b)

Figure 4: SI waveform comparison - voltage divider vs transformer monitoring system: (a) SI 50 %, (b) SI 90 %.



[a] [b]

Figure 5: LI waveform comparison - voltage divider vs transformer monitoring system: (a) LI 50 %, (b) LI 90 %.



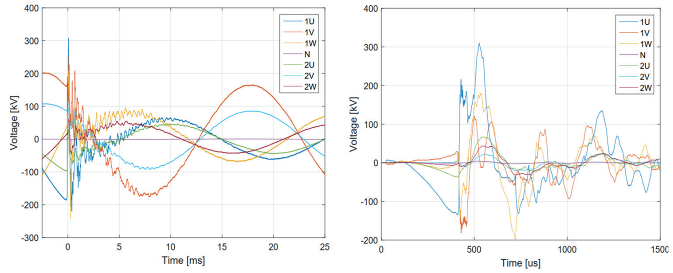
[a] [b]

Figure 6: LIC waveform comparison - voltage divider vs transformer monitoring system: (a) LIC 70 %, (b) LIC 90 %.

Real Case Overvoltage in the Power Network

Generally, overvoltages in power network can be caused by lightning strikes to overhead transmission lines, circuit breaker switching operations and faults. Power transformers can be exposed to such transients during their operation. Overvoltages with steep wave front have an impact on dielectric stress of the transformer's insulation. This can manifest either on the first few windings' turns or, in the case of the internal resonance, the voltage can build up locally inside the winding. The number and amplitude of overvoltages which stress the insulation depend on various parameters, such as the lightning strike density in the considered area, since it determines how often the transformer could be stressed by lightning overvoltages. Since the overvoltage amplitudes at transformer terminals are usually unknown, an on-line overvoltage transient recorder is used with the ability to sample, analyze and store these transients in real-time.

In this paper, three different cases of the overvoltages observed on bushings of a 220/110 kV 150 MVA transformer unit are shown. In Figures 7 and 8, phases are labeled as U, V and W, and "1" and "2" correspond to HV and LV sides, respectively. As the transformer unit is situated in the area with high ground flash density, all three overvoltages were caused by the lightning strikes. In the case 1, double phase to ground fault occurs in the phases U and W as shown in Figure 7 (a) [7].

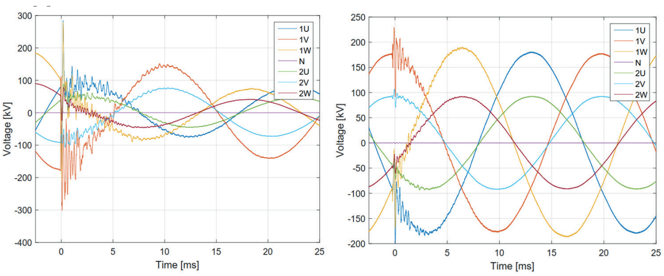


[a] [b]

Figure 7: Transient overvoltages at HV and LV terminals of power transformer – case 1: recorded signals (a) and signals after applying high-pass FIR filter (b).

For further analysis of the impulse signal or usage of the signal in EMTP simulations, it is necessary to filter the impulse from the 50 Hz data. For this, high-pass FIR filter can be used. Applying this filter removes the low frequency and power frequency components of the measured signal [8]. Lightning overvoltage waveforms for the presented case 1, obtained after filtering out low frequency components from measurements, are shown in Figure 7 (b).

Two more cases are observed in this paper and shown in Figure 8. Case 2 represents a double-phase to ground short-circuit on transmission line while case 3 remained without the fault. It is important to note that the overvoltages observed in the power network differ from the standard 1.2/50 μs impulse as they have oscillatory behavior and dominant frequency components in the range from 1 to 30 kHz [7].

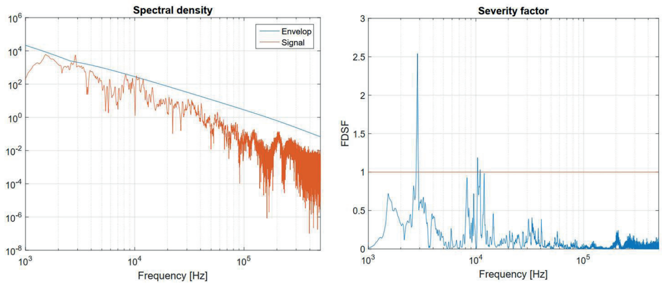


[a] [b]

Figure 8: Transient overvoltages recorded at HV and LV terminals of power transformer – case 2 (a) and case 3 (b).

FREQUENCY DOMAIN SEVERITY FACTOR (FDSF)

In this chapter a Frequency Domain Severity Factor (FDSF) has been explained. It is introduced in order to compare the real impulses with the standard test impulses over the wide frequency band. According to the method described in [2], [9], FDSF is defined as the squared ratio between the spectral density of the measured overvoltage and the spectral density of the standard lightning impulse waveform used for testing transformers. It considers the frequency content of the overvoltages measured in the substation and compares it to the frequency content of voltage waveforms for which the transformer had been tested. The ratio is squared in order to compare the energies of the overvoltages [10]. The FDSF factor should be less than 1 to ensure that the stresses arising from a particular event occurring in the system will be adequately covered by dielectric tests performed in the high voltage laboratory.



[a] [b]

Figure 9: (a) Spectral density (in $[V^2s^2]$) of measured overvoltage versus standard LI and SI; (b) FDSF of the measured overvoltage – case 1.

In the example of the transient observed at 220 kV side of the transformer, the envelope is formed (by taking the maximum) using 100/1000 μs switching and 1.2/50 μs lightning impulses [2] with the amplitude of 850 kV and 1050 kV respectively. Three overvoltages are compared for the FDSF. Prior to the factor calculation, the low voltage signal components were removed as already explained.

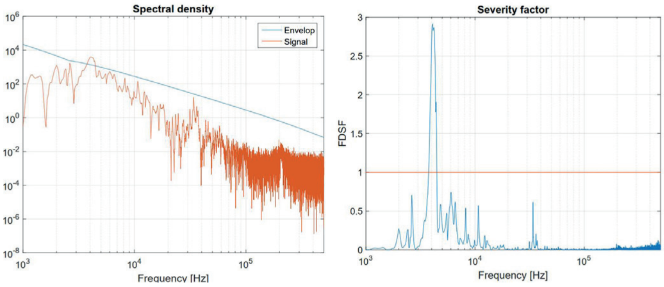
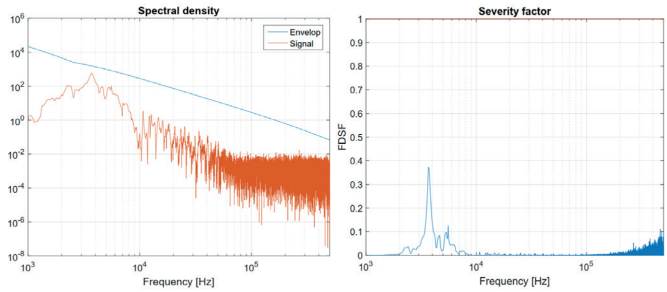


Figure 10: (a) Spectral density (in $[V^2s^2]$) of measured overvoltage versus standard LI and SI; (b) FDSF of the measured overvoltage – case 2.



[a] [b]

Figure 11: (a) Spectral density (in [V^2s^2]) of measured overvoltage versus standard LI and SI; (b) FDSF of the measured overvoltage – case 3.

FDSF exceeds 1 in two out of three observed cases meaning that at these frequencies the electrical stress on the transformer insulation is higher than expected. It also means that transformer tests performed with standard switching and lightning waveforms does not cover adequately low frequency stresses at the range of few kHz. Further step would be to analyze the internal resonance of the transformer windings and to see how these waveforms affect the inner insulation of the winding itself. In some cases of the internal resonances, winding can be endangered if the FDSF exceeds 1.

In general, the FDSF can be used both for design review with regards to incoming transients and in the analysis of failures. When combined with online monitoring, it can also be used as an indicator of increased transient risks for a power transformer.

CONCLUSION

Fleet asset management should have relevant and accurate information when it comes to planning and deciding with regards to strategically important assets such as power transformers and shunt reactors. For that purpose, monitoring systems play an important role since they can collect and process all the relevant data in real time so a quick and factual decision can be made.

Today's state-of-the-art monitoring systems have transient recorders installed in order to have an insight into transformer's/shunt reactor's behavior during such conditions. It is very important to measure transient overvoltages on transformer terminals and to record such events. This can help in assessing an overall condition of an object's insulation system throughout its service years.

Moreover, these effects can be included as input parameters for the health index estimation. This can, in turn, lead to more insight in the current state of the transformer/shunt reactor which will help in decision-making and asset management on the fleet level.

The future investigations in this field can consider correlating the data from the transient recorder with SCADA and LLS systems in order to group the overvoltages by type as well as doing the statistical analysis of amplitudes, frequency spectrum and FDSF of registered events. This can be extended to comparison of non-standard waveforms with equivalent ones in order to develop the method for assessment of the transformer insulation degradation caused by overvoltages.

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Contractors as modern Master Builders: Virtual Design and Construction as an enabler of meaningful experiences to project teams for achieving optimized substation management

SUMMARY

Effective substation management should include engineering and construction costs. While the construction process has to be methodically planned and sequenced to achieve optimized construction costs, substation designers play a vital role for delivering cost-efficient substations. Integrated design and construction has been proposed as a way to achieve effective project management, which historically viewed, was a responsibility of a “master builder”, thus causing Contractors to identify themselves as “master builders”.

As EPC is a highly competitive arena, Contractors are looking for ways to differentiate themselves from their competitors. Some are turning to 3D technologies, while others turn to the design-construction integration. Virtual Master Builder (VMB) supports both 3D technologies and the design-construction integration. Due to a global shortage of worldwide available expertise, Contractors turn to education and training of their employees. While education aims at providing basic skills, training aims to provide the skill necessary to do the job. This paper examines these basic skills as a part of personal mastery before defining organizational learning as a key organizational competence.

Physical Virtuality realm is seen as a fruitful ground for staging of memorable and transformational experiences leading towards achieving “accelerated learning”, and especially 4D models as representations of a “space-time” environment. The project case of Skopje 4 SS 380/110 kV rehabilitation is given as an example of 4D models usage. Project Engineering is seen as a middle ground between engineering and management in order to achieve goals of effective substation management and cost-efficient substation solutions. Project teams are seen as Virtual Design and Construction (VDC) users to achieve these goals.

KEYWORDS

Virtual Design and Construction – Master Builder - Contractor – Substation – Experience – Differentiation – Project team – Project Engineering – Learning - Integration

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INTRODUCTION

Ever since the war of currents started, the race to electrify the world has been accelerating [1]. In 2013, the power sector was reported to be a new dominant sector [2]. In a survey, 77 percent of respondents reported underperforming projects due to various causes, but mainly due to project delays, poor estimating practices and failed risk management processes [2].

Effective substation management, as it was warned, should include all relevant cost factors [3], while engineering and construction costs should be included under the cost of acquisition [4]. As according to [5], the cost reduction of Air Insulated Substations (AIS) should focus on minimizing the construction time and on eliminating mis-sequencing of construction activities, due to negative forces reported such as a shorter civil construction period to build a new substation, and a requirement for a short installation period. For this, a remedy is advised by means of standardizing both design and construction processes and methods [5]. In order to optimize substation costs, attention should be paid on having accurate and detailed engineering and on having experienced and well-trained construction crews, among others [5]. Generally, for risks related to overexpenditures and delays due to miscoordination at site, mitigation in the form of making schedules of manpower and heavy equipment is advised alongside advising monitoring and adjusting time schedules accordingly [6]. Essentially, construction processes have to be methodically planned and sequenced to achieve optimization of construction costs [5]. However, planning the installation of the substation equipment and sequencing it require experience and specialized knowledge [7]. Even though an effective cost and schedule control system is acknowledged to be of a paramount importance for delivering substation construction projects on time and within the budget [8], it has been found out that scheduling, definition of resources and tracking are the least practiced project considerations [9]. Indeed, improper detailed scheduling and planning have been identified as the top factor contributing to the project delay [10]. Improper planning alongside the lacking experience, appropriate skills and knowledge, have been reported as significant reasons for recurring construction problems on substation projects, thus indicating human performance problems in a form of lacking or inadequacy of something [11]. One of the reasons stated inside [11] and related to “inherited problems from the earlier phase” might possibly be related to the engineering stage, as according to [12], design drawings should also describe the construction to be performed. However, while designing for the end state, designers might not take construction steps required to achieve such an end state into account due to lack of on-site experience and / or due to failing to perceive constructability [13]. While effective project management is stated to be the key for delivering “low cost substations” by focusing on cost optimization of a substation as a whole, designers play a vital role in the process of delivering cost-efficient substations in both developing and developed countries [9]. Integrating design and construction was proposed as a method for achieving such goals of effective project management [14]. As design of a substation involves a plethora of interrelated disciplines, necessary expertise, experience and skills must be available inside a project team [9]. Integrated design and construction, in essence, treats construction as one of the technical disciplines of a project team during the design phase in order to ensure constructability of those substation designs [14]. Integration of design and construction, historically viewed, was the responsibility of a “master builder” [15]. The term of the “master builder” is mostly perceived as a term relating to organizations knowledgeable and capable of providing both design and construction services [16], now only infrequently used to describe organizations utilizing the design/build project delivery method which embraces some of the concepts of the master builder approach [15], causing Contractors to identify themselves as master builders [17]. For the energy and heavy industry sector, the master builder approach is reflected through Engineer-Procure-Construct (EPC) delivery method [18], and EPC method is sometimes being referred to as the turnkey method [9].

For substation projects, the turnkey method is most widely used [9]. As EPC is a highly competitive arena [19], Contractors are looking for different ways to differentiate themselves from the competition [20]. Being aware of competitive pressures, organizations are aligning themselves with market requirements, and are embracing 3D technologies for substation design [21]. In order to reduce project duration and installation costs as top reasons to innovate for Contractors possibly will even require changes to be made in the organizational structure, as according to [20]. Gaining competitive advantage through design-construction integration was proposed, based on enabling a transfer of experience within a project team [14]. More effective integration of all project participants has been a goal of Virtual Master Builder (VMB) concept as a digital equivalent to the master builder figure from the antiquity [22]. Is there a way for Contractors to utilize VMB concept to deliver power substation projects effectively, and if so, what are requirements / recommendations to do so?

LITERATURE REVIEW

CHASING THE ELUDING EXPERTISE

The best substation design is seen as one that will most economically and safely supply adequate electric service for both present and future probable loads [23]. In order to design the best substation, the designer should have all the necessary relevant information and be knowledgeable of all potentially viable and applicable substation types [23]. Due to an incomplete set of information, the designer shall use his past experience resulting from similar problems in order to expand such an incomplete set of information, and this ability is usually directly related to the fact how many substations the designer has previously designed [23]. Generally, this number is said to be very small [23].

As reported inside [2], Contractors are aiming for international expansion where they may suffer from inexperience, lack of technical skills and expertise.

Related to the substation design, a lack of the experienced staff was reported to be a major risk factor due to a limited pool of expertise available worldwide [9]. According to [24], “*today’s engineers simply do not possess many of the proficiencies needed to compete internationally*”. In general, at the level of the industry, there is a lack of qualified managerial and engineering personnel [25]. Contractors do report trouble in filling salaried positions of both engineers and project managers, as hiring is reported to be more difficult when compared to a year ago [26]. These staffing challenges mostly result in higher prices in bids and contracts [26].

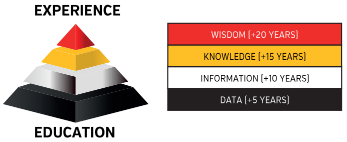

Figure 1. Knowledge pyramid, based on learning ladder from [27]

Figure 2. Rodin's The Thinker sculpture

Figure 1. represents a view of the learning ladder depicted as a traditional Data-Information-Knowledge-Wisdom (DIKW) pyramid, leading from education to experience.

“Acceleration of experience” was being proposed to provide skills and knowledge through learning by conducting a work, but in a faster manner [27]. Similarly, “acceleration of learning” is also being proposed and based on time-compression applied on the learning process [28]. In both cases, final goal is to achieve expertise through experience in a faster manner.

Contractors are also mostly inclined towards initiating or increasing in-house training, and towards providing of career-building programs (education) [26]. While “training” aims to develop knowledge, skills and abilities to do the work, “education” aims to develop critical and basic skills [27]. According to [29], the workforce of tomorrow should have critical thinking skills, complex problem-solving skills, and judgement and decision-making skills.

PERSONAL MASTERY

CRITICAL THINKING SKILL

Critical thinking skill is defined as “*using logic and reasoning to identify strengths and weaknesses of alternative solutions, conclusions, or approaches to problems*” [30]. Deductive and inductive reasoning are two examples of reasoning [31], thus comprising critical thinking.

Term “Renaissance Engineer” is being used as a new vision for the engineer of the third millennium, and there is a tendency for engineering students to undertake some liberal education [32]. Historically viewed, engineering education as such was inseparable from learning liberal arts [33]. Logic, as the art of thinking, represents a natural desire for knowing “the reason why” in a search for the truth, and it is practiced through Trivium, as a part of the seven liberal arts [33]. Other four liberal arts are referred to as the Quadrivium [33].

It is acknowledged that organizations are starting to ask “why” things are done in comparisons to “how” things are done, as they need people capable of critical thinking [27], who should be educated to examine all aspects of the problem critically when facing it [34]. However, disciplinary courses in general rarely provide how, why and what, from a perspective of a larger meaning [35].

Figure 3. depicts three types of single-loop learning, each with its own center of learning.

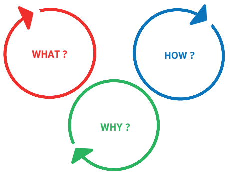

Figure 3. Three loops of single-loop learning [36]

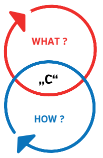

Figure 4. Double-loop learning [36]

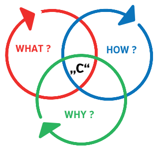

Figure 5. Triple-loop learning [36]

According to [36], learning inside each loop focuses on answering to a specific question, namely: what should we do, how should we do it, and why should we do it. Singe loop learning represents means-end thinking in which ends are set with a goal to discover the best means for meeting those ends, and these single-loop learners are task-oriented [36]. While single-loop learners perceive that identification of ends and the best means to achieve them is not problematic, for double-loop learners the definition of ends and means is problematic, as ends become accommodations or reconciliations among people [36]. Double-loop learning is depicted inside Figure 4. With double-loop learning a new consciousness is created between two centers of learning and is marked as “C”, thus causing de-emphasising of the task-oriented nature in favor of a wider perception of the task [36].

A new consciousness is also created with triple-loop learning for the purpose of being able to operate more intelligently and responsibly through increasing the fullness and deepness of learning [36], and is depicted inside Figure 5. In general, triple-loop learning is also concerned with a wider perception of the task, but with the purpose of creating a fair[er] practice, usually by resolving issues and managing dilemmas when facing them [36]. These issues and dilemmas may arise due to a collision in definition of ends and means as these are treated as non-problematic inside single-loop leaning and treated as problematic inside double-loop leaning.

There has been a reminder that engineering is a service profession which should take into account other factors beyond technical factors such as economic, social, environmental etc. when critically examining a problem [34]. An example of practicing a holistic view of design through different learning loops is given inside Figure 6.

While single-loop learning supports minor fixes or adjustments within governing variables, double-loop learning supports major fixes during which governing variables are usually changed [37]. It is triple-loop learning that goes beyond scientific insight and patterns towards the holistic view of economic, social, cultural and other factors, thus creating a shift in understanding the context or point of view for the purpose of understanding how problems and solutions are related [37].

In essence, multiple loops from Figure 6. converge into a design solution [37].

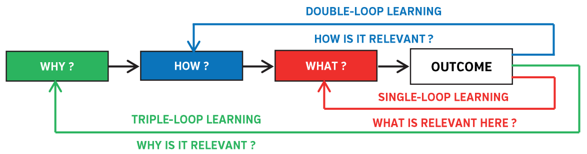

Figure 6. Usage of single-, double-, and triple-loop learning for converging into a design solution [37]

The requirement for double- and triple-loop learning resonates with the role of a design engineer, which according to [9], should study each situation to find an appropriate solution in order to spare resources, but also to learn about alternative available techniques that support realizing the optimum substation design solution. Such unique ideas / solutions leading towards substation optimization are encouraged to be brought forth during brainstorming sessions involving other disciplines as well [38], thus supporting the definition and examining many ideas for substation designs before narrowing it down to a single most cost-efficient one [39].

This is an example of applied critical thinking as both inductive and deductive thinking related to optimization of substation design and construction are practiced. Consciousness in double- and triple-loop learning from Figures 4. and 5. is related to interventionist’s awareness of the centers of learning, thus gaining new information in order to examine prevailing yet unchallenged points of view by means of practicing conscious reflexivity [36].

In Jungian tradition of psychology, the conscious represents what we can know and experience, while the unconscious refers to all that remains beyond our cognitive reach or to that which is unknowable [40]. These two even though diametrically opposed are able to complement each other as the “individuation process” has a goal to integrate the unconscious into the conscious [40]. By “individuation process” we refer to learning process.

COMPLEX PROBLEM-SOLVING SKILL

While complex problem-solving skill is defined as “*identifying complex problems and reviewing relevant information to develop and evaluate options and implement solutions*” [30], conscious problem solving is defined as “*an evolutionary process where actions are taken on basis of an evaluation of alternative scenarios, which is reflection*” [41]. According to [27], engineers are experiential learners. Experiential learning can simply be described as “*the process whereby knowledge is created through transformation of experience*”, through having a reflective observation on a previous concrete experience according to Kolb’s Learning Cycle [42]. Scenarios are defined as temporarily ordered sequences of events, and the richness of alternative future scenarios depends on the richness of past experience [41].

According to [43], many design problems are so ill-defined and complex with uncertainties associated to both, the ends and means of a potential solution. The entire construction process is riddled with uncertainties thus making it an ill-defined problem in its entirety [44]. Available technical tools (the existing professional body of knowledge) are seen as insufficient to manage complicated and complex projects [45], and the project manager alone cannot be a sole hero of a project anymore [46]. “*Artificial tools and methods*” alongside “*Cannot try before build*” are stated to be some of the reasons making construction a risky business [47]. Figure 2. depicts our view of a modern professional when facing ill-defined problems that require solving.

Designers, engineers and managers are reflective practitioners who deal with “messy” situations by means of conducting a conversation with the unique situation at hand trying to make sense of the problematic situation [48]. As the situation is complex and uncertain, there is a problem to find the problem [48]. Constructing and understanding the situation is the first thing to do in order to find the problem by reframing the problematic situation into one dealt with before, as a new problem is seen as a variation of an older problem [48]. It is these built-up repertoires of examples / understandings / actions that are built by previous experiences through practicing reflection-in-action [48]. Reflection-in-action necessarily involves experimentation as an activity to see where the action leads to, but fundamentally answers the question “what if” [48]. In essence, such an exploratory experiment involves experimentation, move-testing and hypothesis testing [48]. Problem solving, as such, is only a part of a larger experiment in problem setting [48]. Reflection-in-action for managers is fundamentally similar to reflection-in-action practiced by designers and engineers for resolving “messes” [48], as sets of interacting problems within complex systems [41].

JUDGEMENT AND DECISION-MAKING SKILL

Judgement and decision-making skill is defined as “*considering the relative costs and benefits of potential actions to choose the most appropriate one*” [30].

Governing variables are defined as preferred states that interventionist strive to “satisfice” when they are acting [49]. These governing variables do not represent deeper underlying beliefs of an interventionist, but do represent variables that can be inferred [49]. Governing variables as deeper beliefs are accustomed to triple-loop learning.

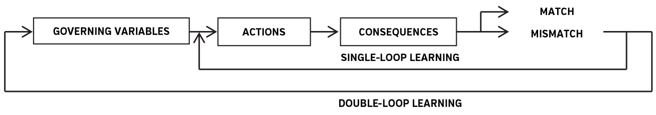

Figure 7. Single- and double-loop learning from the perspective of action-consequence [49]

When a match or a mismatch exists between the preferred state (governing variables) and the consequence of actions exist that is corrected by changing actions, it is said that single-loop learning has occurred in that case [49]. Double-loop learning occurs when mismatches are corrected by examining and altering the governing variables (preferred state) first and then through action [49]. Double-loop learning will be required for a practitioner to solve a complex problematic situation, instead of single-loop learning [50].

According to [51], decision-making process in its simplest form can be described as "*finding the best solution among the set of alternatives having sound preferences that trigger the right course of action*".

For the power substation design, as according to [51], using existing repertoires of action based on the standardization is closely related to the practice of standardized equipment, standardized designs and standard substation layouts, thus relating to agile companies, and namely agile Utilities. This is depicted by the blue line inside Figure 8, which allows deciding stage of the decision-making process to be skipped [51]. It is also argued inside [51] that all other companies differing from agile Utilities cannot skip the decision stage inside the decision-making model, in order to identify the best solution as the most cost-efficient one. Figure 8 is based on Boyd's Observe-Orient-Decide-Act (OODA) loop as a single-agent model for dynamic decision-making, and the Orient stage is of the paramount importance to an entire decision-making model as it "guides" observation of information and "drives" decisions and actions [51]. Lean Project Delivery System (LPDS) is placed at the center of Orient stage, making it a core of a decision-making model when pursuing optimization / cost efficiency [51].

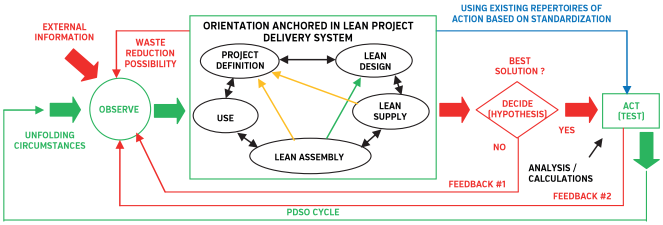

Figure 8. LPDS as a heart of the decision-making model [51]

For the purpose of this paper, a green arrow between Lean Assembly and Lean Design represents application of constructability. In order to arrive to the best solution (with an exception of utilization of the blue line), cycling through feedback loops is inevitable [51].

CORE LEARNING CAPABILITIES FOR TEAMS

While deductive reasoning is largely covered by available scientific tools, available scientific tools still do not cover the majority of inductive reasoning. For that purpose, we assume that individual skills covered inside chapter 2.2. are taken as skills relevant for personal mastery, as according to [52], personal mastery is about seeing the reality objectively.

Figure 9. depicts core learning capabilities for teams and personal mastery is one of them.

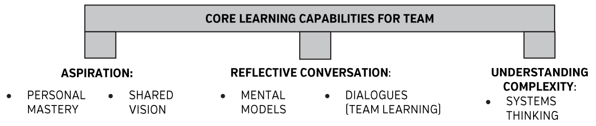

Figure 9. Leaning organization as a three-legged stool for core learning capabilities of a team [52]

Personal mastery is a base for developing of a shared vision which usually represents shared "pictures of the future" that foster commitment [52]. According to [53], people today are no longer satisfied with "just having a job", but are multi-functional, flexible, talented and most importantly, goal-oriented. A move towards self-directed and self-sufficient teams consisting of multi-skilled individuals was proposed to large hierarchical systems as an opposition to demanding compliance [53]. "*Creeping managerialism*" is a problem of today's project management [47]. While the empowering staff has been reported to be the most powerful force behind the substation cost reduction [39], on the other hand commitment was identified as an enabler of a drastic compression in the schedule [38]. Another core learning capability for a team is team learning [52]. Team learning is about developing skills of groups of people to see a larger picture laying beyond their individual perspectives, and it starts with "dialogue" as a capacity of the team to suspend assumptions and get down into genuine thinking together as a team [52]. According to [52], team learning is vital, because teams, and not individuals, represent a fundamental learning unit in organizations. The ability to look at the "big picture" while communicating issues and solutions is identified to be a major contributor to the project success [13]. Project team roles and responsibilities should be clearly defined [9] as TEAM meaning "Together Everyone Achieves More" [53]. Mental models are about perceiving the world and are changed by removing walls between disciplines [52]. Design-construction integration is just one example.

INTEGRATION OF DESIGN AND CONSTRUCTION

According to [54], the project engineer is responsible for engineering and design as depicted inside Figure 10. However, from the same figure it can also be seen that the project engineer is a figure standing in between project manager and design / engineering roles. According to [55], "*Project Engineering is nothing but the integration of all the different aspects of an EPC project*", and is depicted inside Figure 11.

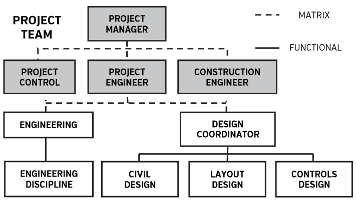

Figure 10. Organization example for small project within utilities [54]

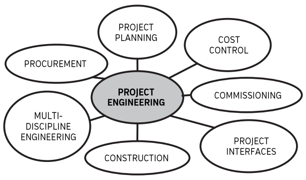

Figure 11. Project Engineering as an integration of all the different aspects of EPC project [55]

Integration of design and construction should involve both, horizontal and vertical integration [14]. While horizontal integration involves integration of different disciplines within the same project phase with the purpose to achieve coordination, vertical integration involves integration of project phases, as according to [14], and depicted in Figure 12. If construction management / engineering is treated as one of disciplines involved in horizontal integration with other technical disciplines, and under vertical integration of design and construction phases, a ground for the most effective application of constructability is created [14].

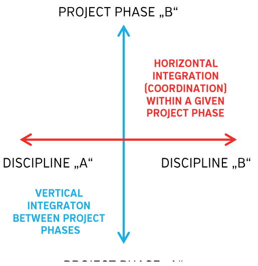

Figure 12. Vertical and horizontal integration of design and construction [14]

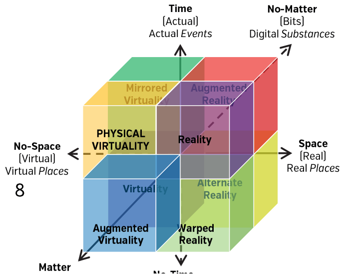

Figure 13. Multiverse concept comprised of eight realms for staging experiences [60]

Constructability requires a balance between design and construction needs, and is interdisciplinary in its nature [56]. As a result, differences between project phases become blurred requiring functional project teams that have a complete project perspective [57]. Constructability as such plays a more prominent role in the new process [58]. New processes should also focus on improving communication among project team members as well [59].

Higher integration of project processes is advised in order to fight one of the problems of contemporary project management, namely "*discontinuity in construction processes*" [47].

OVERCOMING "LEARNING HORIZON" AND THE MULTIVERSE

While personal mastery is seen as an essential cornerstone of organizational learning and its spiritual foundation, system thinking is seen as its capstone that integrates other four core learning capabilities and provides for insights to understand complexity [52]. Within complex systems, decisions and consequences of actions are distant in space and time, preventing in such a way gradual development of learning and maintaining a direct experience as a result of the "learning horizon" [52].

While Senge spoke about "microworlds" as the technology for the Learning Organization [52], Schön spoke of "virtual worlds" for professional practice and development through practice of reflection-in-action [48]. Underlying similarity of both of these "worlds" is the ability to allow "compression of time and space", isolation of variables for experimentation purposes involving cause-effect simulations, move-probing and hypothesis-testing, all conducted inside such a "world" as a risk-free environment, enabling removal of pressures associated with real decision-making in regards to suffering the consequences of selected actions. That are exactly those "worlds" as environments that can provide a unique insight into the future overcoming limitations imposed by the “learning horizon”, and enabling in such a way a development of learning from direct experiences [52].

Organizational learning is regarded as a competence all organizations should develop [49]. Organizations themselves do not learn but are able to create conditions for individuals to learn effectively [49]. Created conditions should support development of double-loop learning [49].

According to the progression of the economic value, services can stage experiences and experiences can guide transformations [60]. When three new axes of “no-space”, “no-time” and “no-matter” are added above axes of “space”, “time” and “matter”, the concept of a Multiverse is created comprising eight realms all of which are capable to stage experiences [60], and those experiences are formed through five human senses [41].

The concept of Multiverse is depicted in Figure 13. The focus of this paper is placed in the realm of Physical Virtuality. “*Instantiating the virtual in the material, Physical Virtuality takes an experience happening in a virtual place and then instantiates, or realizes, it in the real world; first you dream it, then you build it*”, and it is the domain of the Computer Aided Design (CAD) software [60].

PHYSICAL VIRTUALITY FOR SUBSTATION DESIGN AND CONSTRUCTION

It was believed that Virtualization Technology (VT) can reduce the cost of design, construction and maintenance of major facilities such as substations [61]. 3D modelling was seen as a door opening up new avenues for efficient substation construction [62]. Incorporation of three-dimensional modelling techniques into substation design simplifies the design process and allows non-technical professionals to have a better understanding of the design concept [63]. Fly-through and walk-thoughts are helpful for receiving opinions including accessibility and constructability, with a final goal to reduce potential design errors due to unforeseen construction expenses and delays [63]. The construction crew can be thus involved during the design process giving suggestions and helping to identify problems [39], as the coordinated system of construction minimizes the time and the cost required for detailed engineering and field assembly [64]. 3D model-based approach provides means for gaining and exploring “the big picture” for construction crews [58]. As a reduced schedule with a minimized cost has become the predominant theme in most electrical infrastructure projects [63], Contractors should identify all potential delay factors in both, the design and the construction phase [10]. The Contractor can avoid expensive construction problems simulating the construction of the facility and developing a construction plan [61]. 3D models have been seen as an enabler of more optimized construction sequencing [65]. Combining 3D CAD models with construction sequencing facilitates the development of effective substation construction plans through schedule optimization [66].

Design tools enable users to experience differences between options and possibilities through visualization [60]. However, 3D visual design tools are not enough in many situations and should include the fourth dimension of time added onto a virtual 3D model to make experience memorable and transformational when compared to the experience associated to 3D models only [60]. Those models with the time dimension associated to three spatial dimensions are being referred to as 4D models [60].

4D models represent a graphic simulation of the construction process in a determined time unit [67], as 4D model is made from a combination of a 3D model with an activity / task from a Gantt chart [68].

The process of substation construction and installation is suggested as a topic to be included in the training materials [69]. As advised according to [11], recurring construction problems on substations can be resolved using conventional managerial approaches including training and careful planning. Training materials should focus on the topics of how to plan the job, how to develop a realistic schedule, how to develop a detailed estimate and budget, how to track the progress and spot potential problems [70]. Such training materials dealing with real-life requirements for tasks involving design and construction substation projects are mostly not available as “off-the-shelf” products and should be developed internally by the company [70], while being visually enhanced as much as possible [69].

VT has been believed to be an enabler of a greater reduction of costs for training while increasing the productivity of training Transmission and Distribution (T&D) personnel [61]. Building Information Modelling (BIM) tools have allowed engineers to improve their response capacity and provide the faster learning curve for new substation designers [67].

“Accelerated learning” and accelerated training have been reported as advantages of 3D substation design software as these can capture some of the experience of the retired workforce [71]. 3D substation design tools have been seen as a design process improvement [72].

BIM AND VIRTUAL DESIGN AND CONSTRUCTION

3D models are seen as facilitators of interdisciplinary coordination [65], which is stated to be one of the prime benefits of BIM [67]. BIM is also seen as an enabler of a greater collaboration among the design and construction disciplines, but also as a platform for collaboration throughout the project design and construction [25]. In general, BIM has been seen as a “transformational trend” [25], as proven advantageous to project teams [65]. From the context of substation design, BIM is defined as a tool used “*to determine critical cost factors in the early substation planning phase, shift the time, effort and cost structures to earlier phases in the substation planning – enabling better decision making*” [73]. Decision-making models should be transformed leaving behind models of “linear thinking” in favour of embracing shared understanding of interrelationships. In general, decisions are made based on available information / knowledge, thus meaning that management of a construction project is about managing the project information flow [47]. Just “*ineffective information / knowledge management*” is one of the reported problems of the contemporary project management rooted inside a lack of a uniform platform where information / knowledge can be stored and retrieved as wished [47].

According to [74], Virtual Design and Construction (VDC) has been ultimately trying to bridge the expertise gaps between design, construction and operations and is defined as “*an interdisciplinary practice in which data is centralized, typically within a 3D information model, allowing for increased efficiencies and deeper project understanding and analysis*”. VDC processes seek to apply new technologies and to link the work conducted by the members of the project team into the information model, the one that acts as a hub [74].

For VDC practice, BIM is viewed only as an “information model” and two core information models are relevant, namely design intent models and construction models [74]. While design intent models are created for the purpose to visualize and understand the integration of all different systems in 3D space, construction models are created with a greater level of detail to represent what is actually installed [74]. Construction model can also represent the existing conditions for brownfield projects [74].

Generic overview of a VDC practice diagram is given inside Figure 14.

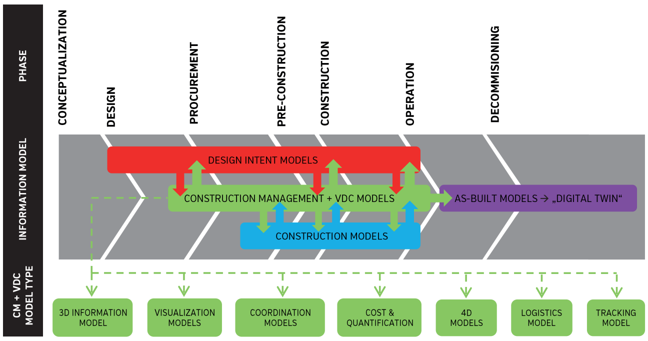

Figure 14. Generic overview of a VDC practice diagram, as based on [74]

Construction management (CM) and VDC models as a mixture of both design intent models and construction models ensure that intended designs are built in the best possible way, at the lowest cost and in the most time-efficient manner [74]. These models include 3D information model, visualization models / experience simulation models (walkthroughs and flythrough), coordination models as a composite model (primarily used for clash detection between systems and for constructability reviews), cost and quantification models (in which quantity information is connected to quantity calculations and then linked to a cost estimation database), 4D models (for visualizing schedule and understanding construction sequencing), logistics models, and tracking models (comparing actual site work progress with planned progress) [74].

The concept of as-built models for operation is similar to a “digital twin” concept.

VDC model types are used as a base for realization of VDC services [74]. According to [74], and depending on a VDC model, these services are typically related to:

- For 3D information model, VDC services may include: model quality control, constructability studies, virtual mockups, field capturing, etc.;

- For visualization model, VDC services may include: experience simulation, contract scope visualization, 3D printing, systems visualization, etc.;

- For coordination models, VDC services may include: design coordination, CM coordination, construction coordination, clash detection, etc.;

- For cost & quantification models, VDC services may include: cost estimating, quantity take-offs, etc.;

- For 4D models, VDC services may include: sequence simulation, 4D scheduling, etc.;

- For logistics model, typical VDC service is related to logistics and site safety modelling;

- For tracking model, typical VDC service is related to progress planning and tracking.

VDC is seen as an enabler of the design and construction integration.

PURSUING EFFICIENCY AND DIFFERENTIATION THROUGH VDC

Organizations aim either at “red ocean” or “blue ocean” competing strategies [75]. While “red ocean” strategies focus on either seeking efficiency through lower cost or seeking differentiation through introduction of marginal innovations, “blue ocean” strategies aim at seeking value innovation by introducing radical innovations [75]. Figure 15. depicts Value level as vertical axis, while five interaction types are represented on horizontal axis, with a demarcation line between “blue ocean” and “red ocean”, all based on [75].

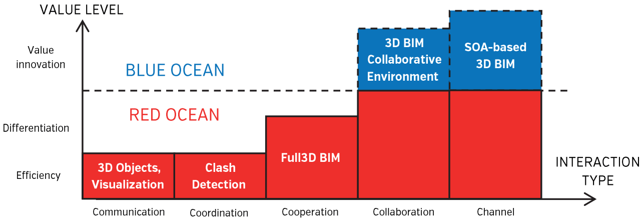

Figure 15. Value level of interoperability for BIM [76], as based on [75]

According to [76], differentiation is achieved through Full3D BIM and Cooperation by focusing on obtaining of time and cost savings through applying construction sequencing and visualizing constructability based on 3D models. Also, costings done directly from a model is defined as an enabler for differentiation [74]. That means that VDC services utilizing VDC models such as cost and quantification and 4D models are classified as enablers for achieving level of differentiation, as per Figure 15. The value of efficiency as according to [76] and seen on Figure 15. is related to utilization of 3D objects, visualizations and clash detection, meaning that value of efficiency is related to usage of VDC models and namely: 3D information models, visualization models and coordination models. Having appropriate information systems set in place is a primary prerequisite for all interaction types [75], here namely for Communication, Coordination and Cooperation. Impact on business processes is expected for interaction types of Coordination and Cooperation, and impact on organizational culture and employees is expected as an impact for interaction type of Cooperation [75].

This means that in order to achieve value level of differentiation through Cooperation by a progress from efficiency (through Communication and Coordination), information systems, business processes, and organizational and employee culture are all impacted [75].

VIRTUAL MASTER BUILDER CONCEPT AND CONTRACTOR’S TO-DO LIST

According to [22], Virtual Master Builder (VMB) concept has been proposed for the following purposes: (1) enabling fully integrated construction process; (2) being an interactive environment for generating plans and designs, critique and evaluate proposals and for conflict resolution; (3) integrating all project stakeholders and participants; (4) supporting integrated framework spanning an entire project cycle; (5) displaying facility model in 3D for gaining a global view on the entire facility; (6) enabling Concurrent Engineering (CE); (7) providing feedback mechanisms and opportunities for innovation and optimization; and (8) providing mechanisms where collective skills of the participants are aimed at a common goal.

The primary objective of VMB is to “*substitute computer-based communication, coordination, and cooperation for organizational control*” [22]. Here we draw a parallel between communication, coordination, and cooperation with these as interaction types from chapter 2.8., but we also draw a parallel between VMB and VDC / BIM, and the following is argued:

- VMB concept is reflected inside a VDC concept;

- Differentiation level is achievable through utilization of 4D VDC models and will have an impact on business processes and organizational and employee culture;

- Business processes should be changed to support integration wherever possible;

- Employees should focus on personal mastery and on developing individual skills;

- Organizations should use collective mechanisms to develop agile project teams;

- Organizational learning is a key competence for delivering substation projects, and;

- VDC is an enabler of “accelerated learning” and of meaningful experiences to all.

Following current trends, the company has embarked on a “differentiation journey” with VDC.

PROJECT CASE FOR SS 380/110 kV SKOPJE 4 REHABILITATION

Skopje 4 SS 380/110 kV was first 380 kV substation to be built on the territory of Republic of North Macedonia during the 1970’s, as a part of former Yugoslavian “Nikola Tesla” 380 kV ring. The rehabilitation scope included replacement of almost all 110 kV primary equipment, replacement of the majority of 400 kV primary equipment, the relay house rehabilitation, rehabilitation of cable trenches and their covers (where necessary), replacement of secondary equipment and of AC/DC systems, with a requirement for installing of a completely new cabling. Due to the difference in today’s standards and regulations compared to ones from the 1970’s, and in order to arrive to the best solution that satisfies all the relevant requirements, a double-loop learning was a necessity due to a requirement for examination of governing variables. These governing variables were related to voltage and safety clearances, sag and wire tension definition, environmental conditions, load combination on the conductors, influence of spacers on the value of forces due to a three-pole short-circuit, etc. Seeking answers relating to what, how and why was a necessity. In order to do so, both 3D substation design intent models and a 3D construction model (depicting existing situation) were created inside “primtech”. Examination of governing variables was conducted inside “primtech” utilizing integrated calculations, interference checks and clash detection. Furthermore, VDC models as a 3D coordination model and 4D model were created for the purpose of conducting constructability reviews and optimizing construction sequencing. Figure 16. depicts a 4D model used for two 110 kV OHL bays with installation process depicted as a green color. Knowledgeable construction personnel were brought up-front with the design team and were treated as a separate technical discipline inside our project team, thus enabling our design team to focus on standardizing designs and materials, supporting ease of installation. As a result, an updated construction methodology document was created and construction activities were defined more accurately. The usage of resources was also defined more accurately, leading to the construction schedule optimization. “Information model” became the project team’s hub.

That has led to connection of patterns not previously linked, as a definition of creativity [41].

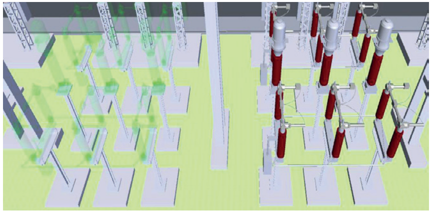

Figure 16. Rehabilitation of each relay house and construction sequencing applied on two 110 kV bays (left and right of relay house)

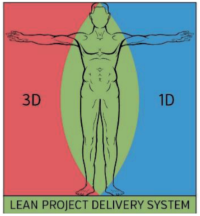

Figure 17. Universal man, as based on geometry from Fig. 8 (b) inside [77]

Creativity is stated as one of the skills required for the future workforce [29]. Let us create...

ADVANCING DESIGN AND MANAGEMENT (ADAM)

The engineer required by the industry of today resembles the “renaissance man”. A 21st century engineer should to be trained for interdisciplinarity. He would need to think in a systems manner [41], and have a breadth of vision [32]. While the “master builder” is about being in charge and in control of all aspects of the project [17], Project Engineering is about integration of these aspects of EPC project [71]. Here, we see Project Engineering as a middle ground between design and construction stage, but also between engineering and management roles. Engineering, like the rest of professions, is a mix of both “art” and “science” [9]. According to [9], “*the “art” of knowing what works best in each situation, which is gained through experience, will guide the “science” to achieve its best results*”. This definition of “art” resembles to definition of art, according to [48], as a skill for action relating to “knowing (reflection)-in-action“. Knowledge as such is a set of mental models [41], which guides the decision-making process [69]. In order to achieve cost-efficient substation solutions, mental models should be aligned with LPDS. For that purpose, we see a man standing on the LPDS body of knowledge on Figure 17. Under definition of “science” we understand the usage of specialized scientific tools. His left hand is immersed into project and construction management professions, while his right hand is immersed into multidiscipline engineering professions, thus utilizing agile decision-support tools to perform tasks inside a dynamic and complex environment. In doing so, he strives to achieve the “unity of opposites” inside of a “space-time” environment, obtaining the “mastery” in his practice through learning-by-doing involving experimentation as double- / triple-loop learning, thus leading to a personal transformation from unnatural and troubled state depicted inside Figure 2. to a natural and self-confident state depicted inside Figure 17. as a representation of the Universal man striving for self-realization following the middle path, one that we identify here as Project Engineering. Figure 17. is based on notes by Vitruvius, Roman master builder.

CONCLUSIONS

Virtual Master Builder (VMB) as a concept for organizational integration through communication, coordination and cooperation [22], is available for project teams through Virtual Design and Construction (VDC) [74]. VDC is seen as a solution supporting effective project management [47], through which problems on substation projects reported inside [11] can be addressed. VDC is seen as an enabler of meaningful experiences that guide transformations towards delivery of substation projects on time, within a budget and of a required performance, supporting recommendations given inside many of CIGRE SC B3 TBs, and especially those given inside TB 740. It is up to Contractors to provide environments, change processes and deal with “organizational defences” to support VDC application on power substation projects, enabling delivery of cost-effective substations by pursuing differentiation. Individual competencies should be translated into collective ones [46].

RECOMMENDATIONS

Future papers on this topic could relate to introduction and utilization of five-dimensional (5D) BIM models (4D + cost) for power substation design and construction. Utilization of 5D BIM models could be put in the context of Value Engineering. Definition of VDC practice diagram and process for power substation projects is also a promising avenue to be explored.

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During 2019 while envisioning the title and the scope of this paper, the authors were inspired by the 40th anniversary of an achievement made in 1979 when the top of Mt. Everest was ascended by opening a new “West Ridge Direct” route, which according to [78], may represent the most difficult route to the top. It is this idea of walking on the edge to balance between emphasised government and efficiency and creativity and responsiveness in organizational systems, which could, according to [79], generate new forms of work and methods of achievement. A fine example of this is a sheer personal willpower coupled with 3D modelling, construction sequencing and various analysis tools, which according to [80], have allowed testing of internal ramp hypothesis on how the Great Pyramid was built. Here we see even triple-loop learning being applied. This paper is dedicated to all individuals, project teams and organizations walking the middle path as a path less travelled.

To knowing oneselves.

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Multicriterial analyses and selection of the best option for revitalization and development of the southern part of Croatian 400 kV network and connection to the power system of Bosnia and Herzegovina

SUMMARY

The southern wing of the Croatian transmission network was constructed for 220 kV in the early 1960's, with additional 400 kV reinforcement at the end of 1970's. Its route of more than 200 km is quite demanding due to extreme climate, environmental specifics and related costs. However, operational experience during more than 50 years has been quite positive. Nowadays, at the end of its lifetime it is again extremely important to analyze and select the best option for network revitalization and development to serve the network users for the next 50 years, but in very different conditions of technological development, more restrictive environmental requirements, electricity market conditions and large scale RES integration. Moreover, special attention should be given to the potential opportunity and need to use this revitalization also for new interconnection to the power system of Bosnia and Herzegovina (BiH).

Altogether with its length of more than 380 km this is one of the largest transmission projects in South East Europe in the last few decades. This paper presents the main findings of the multicriterial and comprehensive study covering technical, economic, financial, geographical, environmental, social and legal assessment, identifying locations of new 400 kV transmission system nodes, internal and interconnection 400 kV lines routes, together with the potential upgrade/replacement of the existing 220 kV circuits.

Network analyses have been prepared on more than 180 different scenarios using PSS/E software, while market analyses were completed for 21 selected scenarios using PLEXOS software. Scenarios were based on the following criteria/uncertainties related to the power systems of Croatia and BiH:

1. analyzed time-horizons (2023 and 2028)
2. demand growth (referent, low, high)
3. analyzed operation conditions (winter/summer peak/off peak load)
4. generation scenarios (high, low, new RES, CO_2 prices)
5. hydrological and climate conditions (average, extreme hydrology and wind speed)
6. power balance (import, export)
7. power transits

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Five main options have been initially selected as topology candidates for problem resolving. Detailed methodology and criteria for the selection of optimal option (revitalization and development scenario and topology) were developed and approved by all involved stakeholders. For selected option, based on comprehensive analyses and approved methodology , for further detailed analyses (system reliability, technical design, investment, economics /CBA/ and environmental analyses) have been prepared, including assessment of its impact on transmission tariffs of each country.

Sensitivity analyses to the most uncertain variables (investment costs and CO_2 prices) were also performed.

The environmental and social assessment was very demanding due to the complex governance structure and three legal frameworks to be respected (two countries, along with two entities in BiH). The Project impact was evaluated with respect to: air quality, water quality, waste management, noise, biological diversity, electromagnetic field, social measures and protected areas.

This paper presents above mentioned analyses, findings and recommendations, as the most comprehensive analytical approach to the transmission line development that's ever been applied in this region.

KEYWORDS

Multicriterial analyses, 400 kV network development, Croatia, Bosnia and Herzegovina (BiH)

PROJECT BACKGROUND

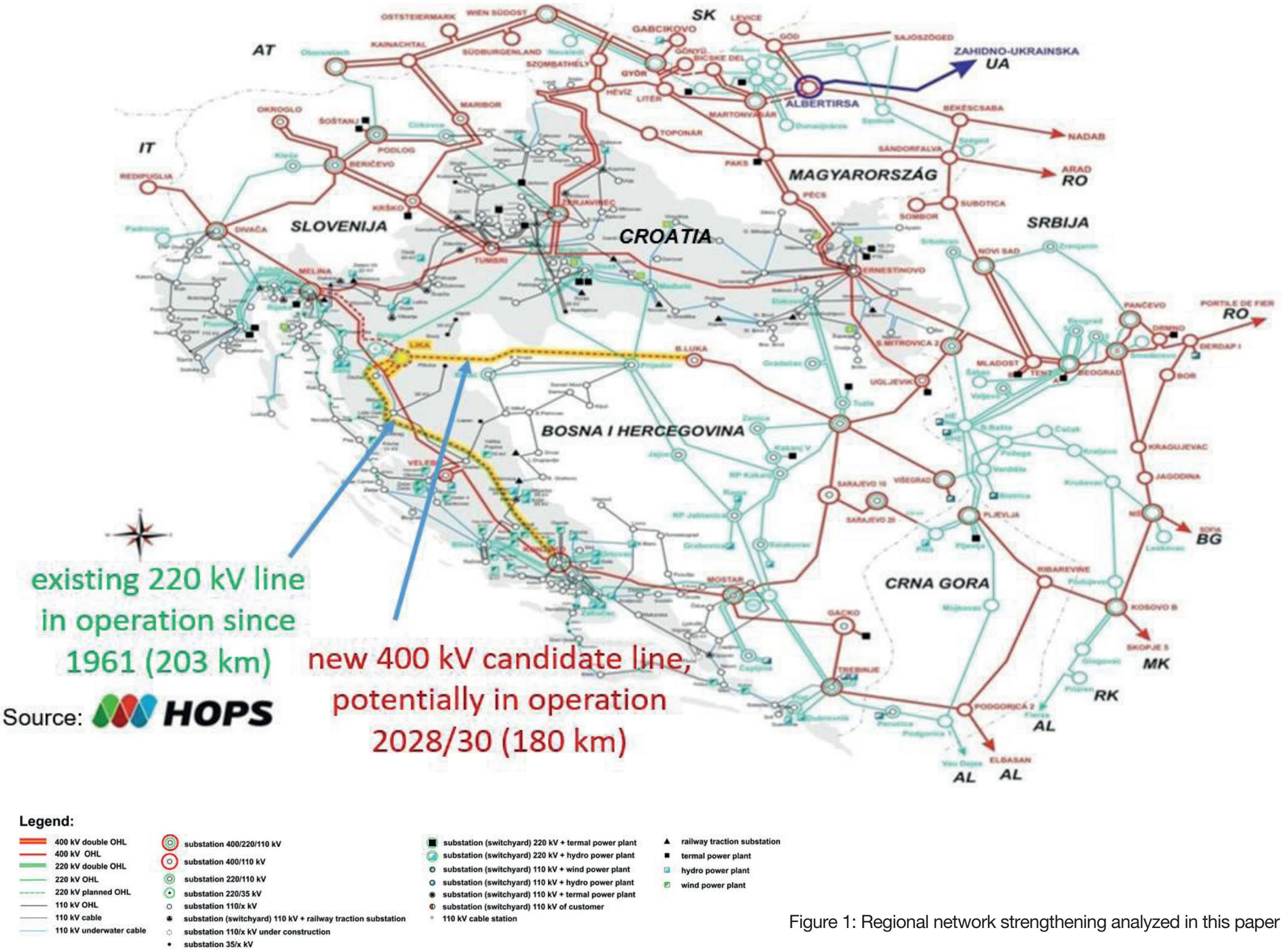
The southern 400 kV and 220 kV wing of the Croatian transmission network was constructed in 1960's and 1970's. It is crucial infrastructure for transmission of large-scale hydro generation located in the south of Croatia and BiH (>2000 MW) to larger consumption areas on the north and further export to the west (Slovenia, Italy). Very positive operational experience with this part of the network in the last 50 years proves that the network planning and project preparation at that time has been done successfully using adequate optimization techniques. However, as lifetime of that infrastructure is close to its end, now it is again extremely important to analyze and select the best option for network revitalization and development to serve the network users for the next 50 years, having in mind that operational conditions are very different from technological, spatial, environmental and economic perspective, including much more uncertainties than 50 years ago. The need for upgrading of the existing transmission network in this area is further boosted in the last few years with huge interest in RES integration (>3000 MW) due to high wind and solar potential.

Therefore, the feasibility study [1] has been launched for strengthening 400 kV transmission line corridor Konjsko – Lika – Melina in Croatia, and new interconnection line to Banja Luka in BiH taking into account existing and expected power system conditions in Croatia, BiH and wider region. The main aim of this analysis was to prepare a full feasibility study for the project comprising of two transmission subprojects:

1. internal line in Croatia and
2. interconnection line between Croatia and BiH

as shown in the following Figure.

The feasibility study [1] resulted with 8 reports (deliverables) on more than 1200 pages and 3 workshops and trainings.



existing 220 kV line in operation since 1961 (203 km)

new 400 kV candidate line, potentially in operation 2028/30 (180 km)

Source: HOPS

Figure 1: Regional network strengthening analyzed in this paper

PROJECT PROMOTERS AND THE SCOPE

Thirteen institutions/companies (promoters and stakeholders) from both countries have participated in this study analysis. Three promoters were divided in two groups:

1. the Client: Croatian Transmission System Operator – HOPS and
2. the Partners:
    - BiH Transmission Company – Elektroprijenos BiH and
    - BiH Independent System Operator – NOS BiH.

Knowing of the project key importance in the future regional electricity system and market development, ten project stakeholders also had important role: EBRD, state environmental agencies, state IPA coordinators, line ministries and regulatory agencies.

In addition to above mentioned 13 institutions/companies, the Consortium of 3 consulting companies also actively participated, preparing all the calculations and the reports. Accordingly, in total 16 institutions/companies participated in this comprehensive activity and project governance, as shown in the following figure. The Client and Partners appointed 22 multidisciplinary experts to support the project, while the Consultants engaged 26 experts. The whole task was carried out by the project team of 48 experts in total. The project lasted for 12 months (March 2018 – March 2019) with 8 meetings in Croatia and BiH.

The scope of the project was:

1. to analyze all potential scenarios of revitalization and strengthening of transmission line corridor Konjsko – Lika – Melina in Croatia
2. to evaluate the need for and assess the feasibility of new interconnection line with BiH
3. to harmonize network development between two neighboring systems, taking into account existing and expected power system conditions in Croatia, BiH and the region
4. to prepare a full feasibility study for the project comprising of two transmission subprojects (internal line in Croatia and interconnection line between Croatia and BiH), using detailed:
    - Technical,
    - Economical,
    - Spatial
    - Environmental and
    - Social assessment.

Figure 2: Feasibility study project governance

MAIN ELEMENTS AND APPRAISAL METHODOLOGY

Five main options have been initially selected as topology candidates related to Croatian internal network for adequate problem resolving. These options were based on different voltage level, line routes and number of circuits in Croatia as follows:

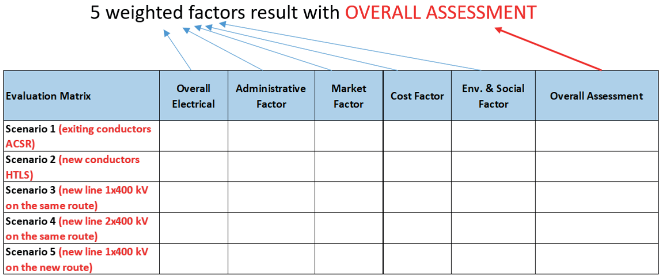
1. Existing OHL 220 kV Brinje – Konjsko with new conductors of the same type (ACSR 360)
2. Existing OHL 220 kV Brinje – Konjsko with new conductors of different type (HTLS conductors)
3. New 1x400 kV using existing 220 kV line route and new SS 400/x kV Lika including in/out of Melina – Velebit 400 kV
4. New 2x400 kV using existing 220 kV line route and new SS 400/x kV Lika including in/out of Melina – Velebit 400 kV
5. New 1x400 kV using new line route to new SS 400/x kV Lika and keeping existing OHL 220 kV Brinje – Konjsko All input data, scenarios and methodologies were approved by the Core Project Team and the Project Steering Committee. The methodology for selection of one optimal scenario was developed and agreed among all stakeholders and it was based on multicriterial approach. This approach relies on five different criteria (factors): electrical, administrative, market, cost and environmental/social (Table 1).

Previously listed topological scenarios have been evaluated through these factors, where each factor has its own weighting factor. Electrical factor was taken as the most important. It was based on the power system analyses in more than 180 different scenarios using PSS/E software package and complete and verified power system model of the whole region of South East Europe taking into account official 10-year network development plans of all regional power systems and the ENTSO-e.

Seven electrical factors have been used in the evaluation matrix:

1. number of scenarios in which a violation of the N criterion is identified
2. number of critical branches identified with respect to N network availability
3. number of scenarios in which a violation of the N-1 criterion is identified
4. number of critical branches identified with respect to N-1 network availability
5. number of scenarios in which a violation of the N-1-1 criterion is identified with respect to 400 kV and 220 kV network
6. number of critical branches identified with respect to N-1-1 network availability with respect to 400 kV and 220 kV networks
7. average power losses for all scenarios

Table 1: Resulting table with evaluation factors



5 weighted factors result with OVERALL ASSESSMENT

Evaluation Matrix	Overall Electrical	Administrative Factor	Market Factor	Cost Factor	Env. & Social Factor	Overall Assessment
Scenario 1 (exiting conductors ACSR)						
Scenario 2 (new conductors HTLS)						
Scenario 3 (new line 1x400 kV on the same route)						
Scenario 4 (new line 2x400 kV on the same route)						
Scenario 5 (new line 1x400 kV on the new route)						

Large number of scenarios (>180) is the consequence of different uncertainties related to the power systems of Croatia and BiH:

1. analyzed time-horizons (2023 and 2028)
2. demand growth (referent, low, high)
3. analyzed operation conditions (winter/summer peak/off peak load)
4. generation scenarios (high, low, impact of new RES, CO_2 prices)
5. hydrological and climate conditions (average, extreme hydrology and wind speed)
6. power balance (import, export)
7. power transits

Every single topological scenario resulted with its overall electrical factor. That value described scenario importance from the electrical perspective.

Market factor used in the evaluation matrix was based on 15 selected market scenarios. Each scenario resulted with country power balance, electricity price, total generation cost and net import cost. Similar as in network calculations, whole South East Europe was modelled using PLEXOS software tool covering 12 regional countries and 4 perimeter countries. The model included 550 generators, 24 interconnection lines and 2 HVDC links, along with complete 110, 220 and 400 kV network in Croatia and BiH.

Market scenarios differ in time horizon, circuit type (HTLS or ACSR conductors), CO_2 price variations, with or w/o link to BiH. Special emphasis in market analysis was given to EUCO 2030 scenario prepared by the European Commission and presented in the ENTSO-E TYNDP 2018. It provided additional overview of expected European energy future up to 2030 and beyond.

Administrative factor used in the evaluation matrix assumed complexity of formal project development procedures for each scenario. This factor can have two values: "yes" (it is feasible in given timeframe) or "no" (not feasible in given timeframe). Based on the construction practice and formal procedures and deadlines in Croatia it is not feasible to prepare and build new 400 kV line using new 200 km long route in just 5 years. Therefore, these options were evaluated with negative administrative factor.

Cost factor used in the evaluation matrix reflected estimated construction cost for given topological scenario, while environmental and social factor used in the evaluation compares environmental and social risks.

The best topological scenario for each evaluation factor is awarded with 10 points, while other scenarios are normalized to that value. Weighting factors for each factor were based on its importance and have been approved by the project team, as given below in the table. Linear combination of evaluation factors and its weighting factors results with overall assessment value for each topological scenario.

Large number of scenarios covered a majority of all expected power system regimes and uncertainties in both countries, including additional sensitivity analysis in economic assessment. Accordingly, the study results can be taken as proven on the adequate set of input data, scenarios and assumptions, as well as adopted and harmonized between two neighboring system operators.

SCENARIO COMPARISON ANALYSES

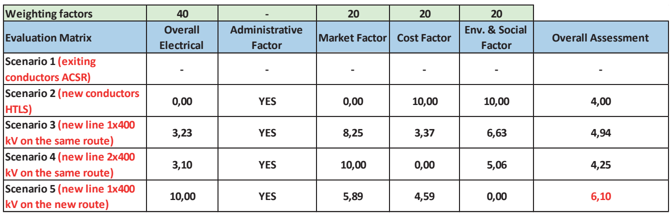
Based on the above-mentioned criteria and methodology scenario evaluation matrix for 2023 is given in the following table. The largest overall assessment value in 2023 is given to scenario 2 – existing OHL 220 kV Brinje – Konjsko with new HTLS conductors. Scenarios 3, 4 and 5 are estimated as not feasible till 2023. So, for short-term time frame scenario 2 is evaluated as the best option, having the best overall electrical and environmental & social factor (using existing route, so with no additional environmental impact), very good cost factor, but quite low market factor.

Table 2: Scenario evaluation matrix for 2023

Weighting factors	40	-	20	20	20	
Evaluation Matrix	**Overall Electrical**	**Administrative Factor**	**Market Factor**	**Cost Factor**	**Env. & Social Factor**	**Overall Assessment**
Scenario 1 (exiting conductors ACSR)	8,32	YES	0,00	10,00	9,00	7,13
Scenario 2 (new conductors HTLS)	9,67	YES	0,80	9,07	10,00	7,84
Scenario 3 (new line 1x400 kV on the same route)	0,56	NO	8,53	3,31	6,63	3,92 (not feasible until 2023)
Scenario 4 (new line 2x400 kV on the same route)	0,00	NO	10,00	0,00	5,06	3,01 (not feasible until 2023)
Scenario 5 (new line 1x400 kV on the new route)	10,00	NO	3,86	4,51	0,00	5,67 (not feasible until 2023)

The same approach was used for 2028 timeframe in two sub-scenarios: without and with new interconnection to BiH, as given in the following two tables. The largest overall assessment value for 2028 without OHL 400 kV Lika – Banja Luka is given to scenario 5 – new 1x400 kV using new line route to new SS 400/x kV Lika and keeping revitalized OHL 220 kV Brinje – Konjsko (including in/out SS 220/x kV Krš Pađene). All scenarios are feasible till 2028, having positive administrative factor. So, for longer-term time frame scenario 5 is evaluated as the best option, having the best overall electrical factor, acceptable cost factor, but lower market factor and the lowest environmental & social factor (using new route, so with the largest environmental impact).

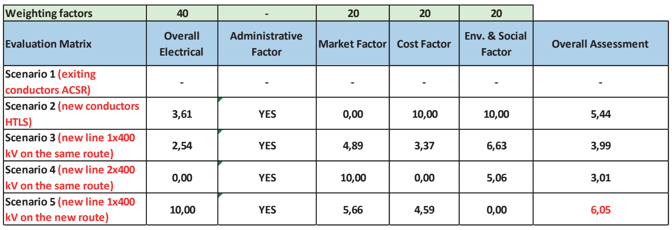
Table 3: Scenario evaluation matrix for 2028 without new interconnection Croatia – BiH



Weighting factors	40	-	20	20	20	
Evaluation Matrix	**Overall Electrical**	**Administrative Factor**	**Market Factor**	**Cost Factor**	**Env. & Social Factor**	**Overall Assessment**
Scenario 1 (exiting conductors ACSR)	-	-	-	-	-	-
Scenario 2 (new conductors HTLS)	0,00	YES	0,00	10,00	10,00	4,00
Scenario 3 (new line 1x400 kV on the same route)	3,23	YES	8,25	3,37	6,63	4,94
Scenario 4 (new line 2x400 kV on the same route)	3,10	YES	10,00	0,00	5,06	4,25
Scenario 5 (new line 1x400 kV on the new route)	10,00	YES	5,89	4,59	0,00	6,10

The largest overall assessment value for 2028 with OHL 400 kV Lika – Banja Luka is given again to scenario 5 – new 1x400 kV using new line route to new SS 400/x kV Lika and keeping revitalized OHL 220 kV Brinje – Konjsko (including in/out SS 220/x kV Krš Pađene). This scenario has again the best overall electrical factor, good cost and market factor and the lowest environmental & social factor.

Table 3: Scenario evaluation matrix for 2028 with new interconnection Croatia – BiH



Weighting factors	40	-	20	20	20	
Evaluation Matrix	**Overall Electrical**	**Administrative Factor**	**Market Factor**	**Cost Factor**	**Env. & Social Factor**	**Overall Assessment**
Scenario 1 (exiting conductors ACSR)	-	-	-	-	-	-
Scenario 2 (new conductors HTLS)	3,61	YES	0,00	10,00	10,00	5,44
Scenario 3 (new line 1x400 kV on the same route)	2,54	YES	4,89	3,37	6,63	3,99
Scenario 4 (new line 2x400 kV on the same route)	0,00	YES	10,00	0,00	5,06	3,01
Scenario 5 (new line 1x400 kV on the new route)	10,00	YES	5,66	4,59	0,00	6,05

According to adopted methodology and criteria suggested revitalization strategy for the timeframe of 2023 is replacement of the existing conductors at the OHL 220 kV Konjsko - Brinje with the new HTLS conductors. For 2028, the construction of new 400 kV line(s) Konjsko – Lika – Melina was suggested as the optimal scenario, no matter with or without new 400 kV interconnection Croatia - BiH.

For selected optimal scenario further detailed technical design, economics and environmental analyses have been prepared. Clearly, the main driver for selected network reinforcements in 2023 and 2028 was planned new RES generation development, including additional 841 MW (low generation development scenario) to 2924 MW (high generation development scenario) in Croatia till 2028, as well as 2509 MW (referent generation development scenario) to 2962 MW (high generation development scenario) in BiH.

New interconnection line 400 kV Lika (Croatia) – Banja Luka (BiH) should be commissioned if market conditions are going to be favorable for this line (for example large export from BiH or import to BiH due to real market conditions which will be strongly determined by CO_2 emission price in the future).

SELECTED OPTIMAL SCENARIO ANALYSIS

For selected optimal scenario additional detailed analyses have been taken, including:

1. network analyses (load flow and (n-1) security analyses, short-circuit calculations, transmission losses evaluation (annual electricity losses in transmission network of Croatia and BiH, TTC/NTC calculations for Croatia/BiH border in both directions, voltage profile analyses, reliability assessment, transient stability analyses),
2. market analyses (overview of countries electricity balance in the region (production, consumption and exchanges), electricity prices for each country, total generation cost for each country, amount and cost of CO_2 emissions for each country, cross-border power exchanges for each interconnection in the region),
3. cost-benefit assessment – CBA (socio-economic welfare (SEW), cost of losses, security of supply, reactive power compensation and voltage control),
4. technical design (line routes, substation locations, expected climate conditions, towers, foundations, conductors, earthwires, insultation, grounding and supporting equipment),
5. environmental impact assessment (legal and institutional overview, gap analysis, environmental scoping, impact assessment in Croatia and two entities in BiH),
6. impact on transmission tariffs in both countries.

Due to limited available space only the most important outcomes are given in the concluding remarks of this paper.

CONCLUSIONS

CBA was performed for selected optimal scenario in 2028 (scenario 5) primarily on the principles established in the “2nd ENTSO-E Guideline for Cost-Benefit Analysis of Grid Development Projects” (Guidelines) [2]. Results of the cost-benefit analysis have shown that the benefits of the project to the society greatly outweigh the costs in the base case scenario. All calculated economic indicators have resulted in positive values, including ENPV and ERR. In the additional EUCO 2030 scenario, the project variant of OHL Lika-Banja Luka has resulted in negative profitability, which is a direct result of a much smaller socio-economic welfare benefit calculated in the market analysis.

Sensitivity analysis to the most uncertain variables was performed, i.e. to the change in investment costs and CO_2 prices. Investment costs were varied by 10% and 20%, while CO_2 prices were varied in the market analysis and the resulting SEW was taken into consideration for calculating new economic indicators with these results. Sensitivity analysis performed on investment costs has also shown positive results for the 2028 scenario, both with up to 20% decrease and 20% increase in investment costs. However, not even a 20% decrease of investment resulted positive for OHL 400 kV Lika-Banja Luka in the EUCO 2030 scenario. Sensitivity analysis performed on CO_2 prices has shown that an increase in CO_2 prices would have positive impact at the results in all project options.

Technical design resulted with detailed assessment of the line route for OHL 400 kV Konjsko – Lika (203 km) and OHL 400 kV Lika – Banja Luka (53 km in Croatia and 127 km in BiH), altogether 381 km. Technical design for the existing and new substations was also prepared.

Environmental and social assessment was very demanding due to complex governance structure and three legal frameworks to be respected. The Project impact was evaluated in: 1) pre-construction and construction phase, 2) operational phase and 3) decommissioning phase with respect to: air quality, water quality, waste management, noise and vibration, biological diversity, electromagnetic field, social measures and protected areas. Final results proved that this project can be realized with minimal environmental impact avoiding protected areas and fulfilling all legal requirements. Relevant documents have been prepared for further formal steps in issuing environmental consents in both countries.

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Advanced and Rapid Tool in Control Room to Determine the Cause and Location of Events in Transmission Network

SUMMARY

Operating personnel in control room act on SCADA alarm generated on data from station computer. Using new technologies and advanced technical solutions assistance tool can be designed. This tool provides quick help in busy situations for operator. For this new tool with three types of case studies insight will be given in this paper. Introduction part has short information about numbers of alarms and events in Control centre, and their distribution during one month period. Basic principles for alarm handling in SCADA system is given with all limitations. New tool, Intelligent Alarm Processing system is designed and implemented in control room. It has connection to SCADA system with standard data exchange format CIM/XML and run in real time, with only few seconds delay. This system based on Multilevel Flow Model has root cause analyses implemented for power system. Detail fault location algorithm description with block scheme for this Intelligent Alarm Processing system is part of third chapter. Special attention must be paid for modelling protection data in SCADA system which are sent to this new tool. Demonstration of Intelligent Alarm Processing system operation is reported in fourth chapter. Three characteristic disturbances in transmission network were elaborated. Most complex and challenging disturbances for operator in control room is cascading event. This case study is presented in detail in four sequences through graphical user interface. Second case study is also challenging for operators, heavy winter storm with numerous isolated events. In this case study very effective graphical presentation and alarm list with three types, primary event, consequences and detail list for this events were demonstrated. This list pointed out exactly and clearly what happened in the network. Last case study presents common disturbances which appears on daily basis, where this tool is of great assistance because it points on transmission elements very fast.

KEYWORDS

Intelligent alarm processing, control room data processing, root cause analyses, IAP, SCADA, control centre, alarm management, CIM/XML, operator assistance during disturbances

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INTRODUCTION

The Transmission System Operator Company (HOPS) uses one SCADA system for monitoring and control function and for maintenance purposes [1]. Data inflow in control room are increased during operating hours and during disturbances as shown on Figure 1. Number of alarms at the Regional control center Osijek, in October 2019.

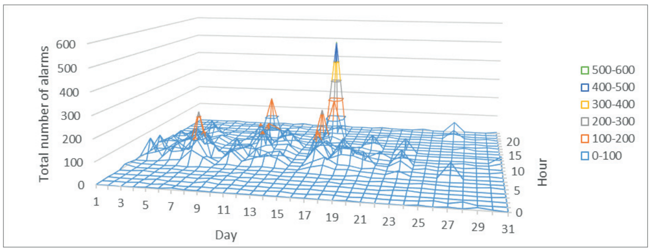


Figure 1. Number of alarms at the Regional control centre Osijek, in October 2019.

In order to investigate the alarm load situation, the actual alarm rates are constantly measured and monitored. On Figure 1., number of alarms at the Osijek area Regional control centre in October 2019 are presented. The x-axis shows 31 days in the month October, the y-axis shows 24 hours, and the z-axis shows the number of alarms. The alarm rate curve is not uniform during day and night. Generally, for all area control centres, the alarm rate is highest during working hours (08:00-16:00). It should be noted that during this period, the alarms were mainly caused by maintenance work. Modern TSO's have advanced technologies in control room and combine them to create many smart grid applications for daily business process [3]. One relatively new tool for helping to have better power system visibilities during massive data inflow is Intelligent Alarm Processing (IAP) system.

EVENT AND ALARM MONITORING IN A SCADA SYSTEM

Alarm monitoring and presentation in a SCADA system is limited to basic functions:

- Priority classification and colouring.
- Grouping of alarm and events based on assigned classes.
- Alarm and event list filtering.

In most SCADA systems, there is no possibility to present group alarms or events in event lists based on network element connection or to use sub lists. The only possibility is to present individual alarms or events and to use predefined filtered lists. Static grouping of alarms is possible, but it requires a large amount of engineering work and lacks "drill down" support. Each event is presented in its own line, and in case of larger disturbances in the system, due to a large number of events, it could be difficult for the operators to locate the event which points to the root cause even, in pre-filtered alarm lists. Different event presentation types used in SCADA systems are described in Table I, [2].

Table I. Presentation of events in a SCADA system.

Priority coloring	Alarm grouping	Pre-filtered list
HIGH MEDIUM LOW	Trip events and alarms Breaker status Disconnector status Active power limit Protection relay failure Transformer failure	Breaker switching events & protection trips Active power limit violations Reactive power and voltage limit violation

INTELLIGENT ALARM PROCESSING TOOL

General description

An intelligent alarm processing (IAP) tool was integrated with the SCADA system in the control room using CIM/XML standard exchange format for data exchange of the network model, and OPC DA (Open Platform Communication, Data Access) and A&E (Alarms & Events) interfaces for alarms and events exchange in real time. During 2016, the IAP system was upgraded. The new version has its own web interface and MONGO database. The alarm processing method is based on MFM (Multilevel Flow Model) models and a root cause algorithm applied to power systems. The basic objects in the model are generators, lines, buses and loads. The model is automatically built from the imported network model. IAP is an operator support tool. It reads discrete and analog grid data, such as alarms, events, and analog signals, and provides automatic analysis to help the operators in the control room to understand the current fault situation in the grid. Main tasks are situational awareness, alarm grouping, and root cause analyses.

Fault location algorithm

This paper reports the experiences of a software system using intelligent alarm processing and real-time root cause analysis of complex alarm situations. The system provides an alarm management technology with the following functions.

- SCADA alarms from a single grid object (generator, transmission line, busbar, etc.) are grouped into single alarms, so the operator easily can see which objects have problems or are out of service.
- Nuisance alarms that are activated repeatedly over short time periods, so-called "chattering" alarms, are monitored by the system and shelved and un-shelved dynamically. Shelving means that the alarm is moved from the primary alarm list to a separate list for shelved alarms.
- Other alarms are caused by damaged or unused equipment and remain active for a long time, so-called "long-standing" alarms. These are also monitored by the system and are timed out after a fixed time period, currently four hours.
- The system contains a model-based algorithm that can analyse consequential alarm cascades and show the root cause alarms ("the real faults") in a primary list, and consequences in a secondary list.

For readings on intelligent alarm processing with on-line root cause analysis, see [4-11]. The combination of these methods leads to a large improvement of the alarm situation. In complex fault situations, hundreds of alarms may be shown in the SCADA system, while the IAP tool only shows one or two primary root cause alarms. The alarm management algorithm uses knowledge of the physical structure of the power grid, which it acquires from a SCADA/EMS network model. At HOPS, the internal IAP model is derived from the existing CIM XML description of the SCADA/EMS network model. The algorithm also uses operational real-time data from the synchronized SCADA system database, such as analog and discrete signals (power flow, voltage, amps, breaker and disconnector positions, and protection signals), and the real-time alarm and event stream, see Figure 2.

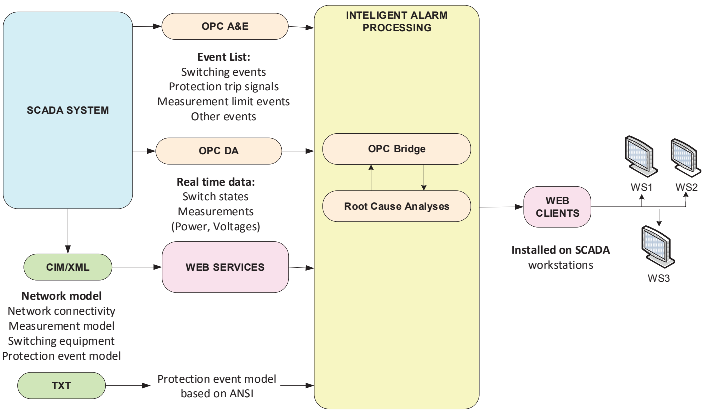


Figure 2. The IAP software integrates with the existing SCADA/EMS system.

All grid knowledge used in the calculations can be derived automatically from the CIM model. Whenever the CIM model is updated, it is imported to the system and compiled, which takes less than a minute. This means that the system needs no manual maintenance.

The real-time functionality consists of several software layers, which perform calculations on analog and discrete data to identify stale signals, bad data, delta changes, equipment which is out-of-service, faults states, and the global root cause analysis state for the whole transmission network.

The intelligent alarm processing system is a separate software application that can be integrated with a SCADA system in several different ways. It consists of a central server and one or several clients. The server executes on a separate computer. The server receives real-time data from the SCADA system via network protocol. The results of the analysis for the whole network are stored in the server and are distributed to all clients in all control centers in real time, see Figure 2.

The system uses alarm grouping and root cause analysis. It presents its analysis in a graphical grid overview and in a set of intelligent alarm lists. The IAP system groups all SCADA alarms that belong to a single grid object into one single alarm message. In this way, it becomes easier to see which grids objects have failed.

For example, a transmission line which trips may trigger several alarms, such as:

- Breaker open alarms from both ends of the line.
- Zero voltage alarms.
- Zero megawatt or zero ampere indications.

Modelling of protection data from SCADA for IAP

To give the model better results [12], additional efforts have been made to the basic intelligent alarm processing algorithm, with a relay protection model and real time protection data from the SCADA system. In the analysis, it is important to distinguish the relay protection function that isolated the failure on network element where the problem appeared, from the protection function that tripped to isolate the disturbance in other parts of the network due to overload or malfunction in the primary protection. All relay protection trip signals in the SCADA system are classified and associated with ANSI codes. The IAP tool uses these codes to determine the location of the fault based on protection function logic (see Figure 3). The fault network element is pointed out in the transmission network scheme using a red arrow and simultaneously displayed in the primary alarm list created by the IAP system. The source of the protection signal list (file) is a unified database according to the HOPS codebook to which ANSI codes are associated [1]. The relay protection functions for determining the primary failure in the network are shown in Figure 3 and are an integral part of the IAP application module.

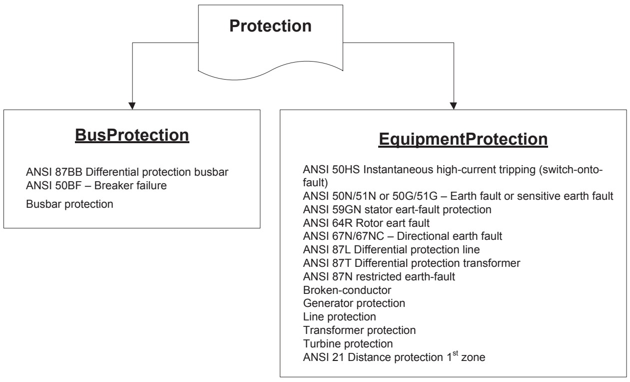


Figure 3. ANSI codes and protection functions used in the IAP analysis

According to the above, the basic data for the analysis are data from bus protections, protections of network elements (transmission lines, transformers and generators) and earth-fault protections. For the purpose of IAP analysis, there are three basic groups of relay protection trip signals according to the location of the failures:

- Independent failures in the transformer station itself. This group includes bus protection signals and breaker protection signals.
- Independent failures near the transformer station. This group includes earth-fault protection signals for transmission lines, differential protections, and tele-protection signals.
- Independent faults not near the transformer station. This group includes all other protection function signals.

CASE STUDY FROM CROATIAN TSO NETWORK DISTRUBANCES

Croatian highvoltage transmission network – basic facts

Croatian TSO has around 8.000 kilometres lines and 190 highvoltage substations (400 kV, 220 kV and 110 kV), Figure 4. Signals from all station computers are connected to SCADA system in control room, which means more than 100.000 indications, commands and measurements are inflowing in control room.

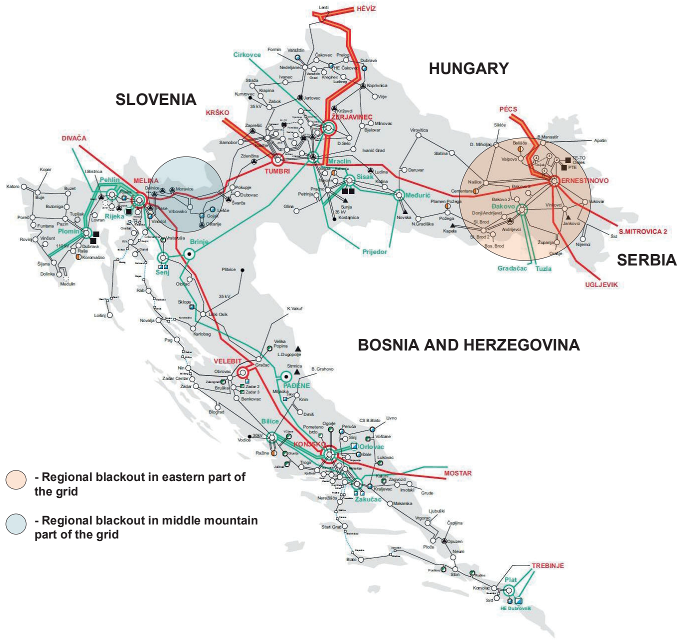


Figure 4. Croatian highvoltage transmission network

Two case study for IAP operations will be presented in this chapter. First, one is a cascading event, which cause regional blackout in eastern part of the network. Second event is from mountain part during local heavy winter storm with ice and snow.

Cascading event in the eastern part of transmission system

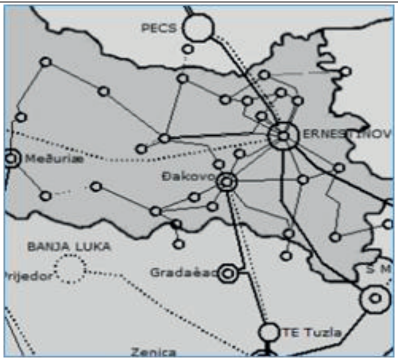
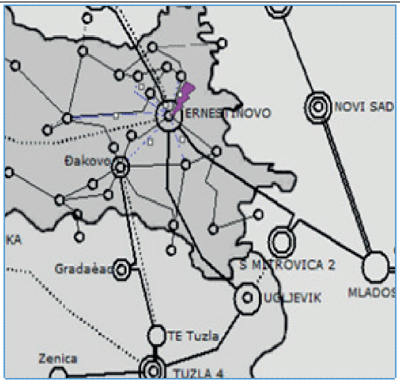
DESCRIPTION OF EVENT AND FAULTS

The substation SS 400/110 kV Ernestinovo is a main point of supplying the transmission system region Slavonia with electrical energy. SS Ernestinovo, with 5 tie lines on the 400 kV level, is very well connected with other parts of the HOPS grid and neighbouring TSOs. Inside the SS, there are two transformers of 400/110 kV and 10 tie lines on 110 kV level. On the 14th of May, at 8:18 am, due to a technical error during maintenance, busbar protection on the 110 kV level disconnected all elements connected to one of two 110 kV system busbars. A few of the 110 kV and 220 kV tie lines were overloaded and tripped as consequences. The final state was that 20 substations lost voltage.

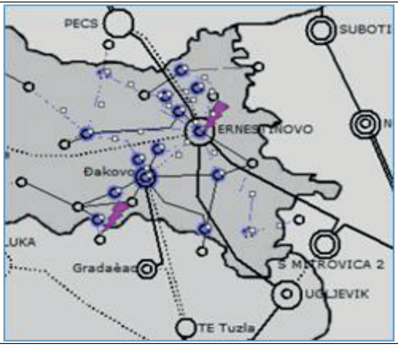
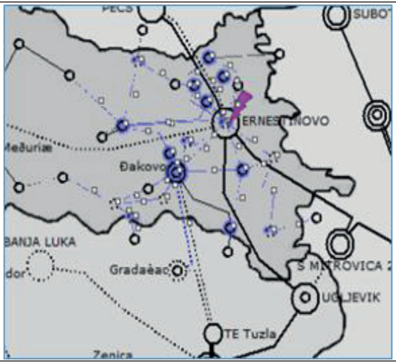
The initiating event was a power transformer trip in the 400 kV Ernestinovo substation. Subsequent analysis by HOPS identified that one busbar protection relay on the 110 kV side of the Ernestinovo substation was triggered, effectively clearing one of the main buses. About three minutes after the initiating event, an important transmission line at the 220 kV level south of SS Ernestinovo tripped. This in turn led to a regional voltage collapse with several line trips until stable conditions were reached.

INTELLIGENT ALARM PROCESSING

Short presentation will be given in this chapter with screenshots from IAP system. In four slides in one sequence order IAP system will be presented and how it works in real time.

Grid state at: 08:18:18 a.m.	Normal operating conditions in eastern part of transmission grid. Outaged lines are presented with dotted line. Ernestinovo is key point for supply of the region. 220 kV grid was slightly weakened in Đakovo substation. One line was in maintenance. This fact will drive to voltage collapse case in second part of this cascading event.	
Grid state at: 08:18:59 a.m.	Due the combination of maintenance and technical error, busbar protection on 110 kV level tripped one system in main supplying substation. Root cause is marked as a purple arrow pointed on 110 kV circle. Blue lines are lines without voltage, while consequences are marked with small, white dots. From that moment grid was weakened and starts to glide to point of no return .	

After this fault which was classified like a root cause in IAP system, cascading event takes place in next four minutes. The event has two main characteristics, line overloading and fast voltage collapse induced by sequential operations of on load tap changer. These tap changers operated on grid power transformers 220/110 kV in order to maintain the voltage in 110 kV grid.

Grid state at: 08:21:49 a.m.	Cascading events rolled further. New primary event happened and purple arrow appears on 110 kV line which was overloaded. This event was temporary presented. New lines and transformer were tripped and put in blue (no voltage). Đakovo substation was tripped during very short voltage collapse.	
Grid state at: 08:22:49 a.m.	Finale stage of cascading event. The bus-bar protection is identified as the root cause and the other 82 events are shown as consequences. 400 kV grid stayed in operation. IAP operated in timely manner.	

SCADA ALARM ANALYSES

A comparison of the data arrived at the SCADA system and the IAP is given in Table II, for the period from 08:18:48 to 08:26:25 a.m.

Table II. Number of disturbance events.

SCADA		IAP	
Event list	SOE list	Primary event	Consequences
2094	533	2	82

SCADA system collect and generate numerous events in Event list and detail events inflow in Sequence of Events (SOE) list. This last list is essential for later off line analyses.

Isolated fault in mountain part of transmission network

Description of the Event

In February 2014, due to snow and icing, a serious disturbance in transmission grid occurred in the region of Gorski Kotar. Due to a damaged 110 kV tie line Delnice-Vrata, the substation 110/35/20 kV Delnice was radially supplied through the 110 kV line Delnice-Moravica. On 12th of February 2014, at 10:36 am, the IAP system registered the primary event of a mutual failure on the 110 kV line Delnice-Moravica.

The primary event was triggered by relay protection on the transmission line at Delnice SS (permanent fault on the transmission line) and consequently three transformers tripped off. Figure 5 shows the primary event due to transmission line failure (arrow on white-shaded transmission line) and secondary events (small white dot in the SS Delnice facility).

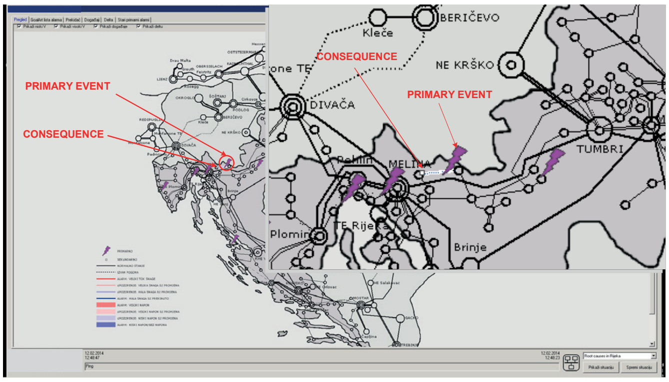


Figure 5. Graphical display of event on February 12, 2014 at 10:36 am

In the alarm list, as a result of the analysis, Figure 6 shows the primary event for the 110DELNI-EVMOR object out of operation and the protective relay active and the secondary events, transformers in SS Delnice out of operation: 110TR1_2, 110TRA and 110TRB. The details window shows us the signals from the SCADA system grouped into objects that are topologically related to the specified event.

During the analysis of this disturbance, the model worked properly and classified events by cause and effect. The result of the model analysis is one primary event and three secondary events, with a total of 64 process signals recorded in the SCADA system.

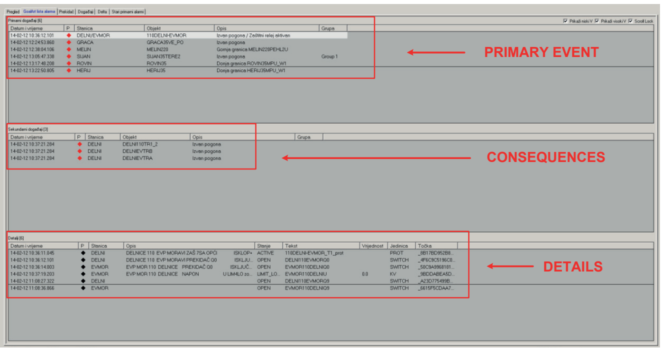


Figure 6. Alarm list of event on February 12, 2014 at 10:36 am

Use case as daily monitoring of situation

In order to describe the principles of grouping and presentation of the event in IAP in comparison to the SCADA system, a simple protection event will be described with only one power line tripped on 3th of January 2020 at 15:04:41. The event was caused by an unknown and undetected reason and distance protection tripped the power line. During the period from 15:01:11 to 15:04:51 there are 238 registered events from protection relays, switching states and auxiliary power supply in the SCADA event list. The intelligent alarm processing application presents the alarms under one primary event, which is presented in the event lists as shown in Figure 7:

- Time: 15:04:41.641.
- Station(s): *LUDBRE/HECAK*.
- Name of the network element: *110HECAK-LUDBR.*
- Text - event description: outage (*Izvan pogona*)/Protection event (*Zaštitni relej aktivan*)/Voltage state (*Nema napona*).

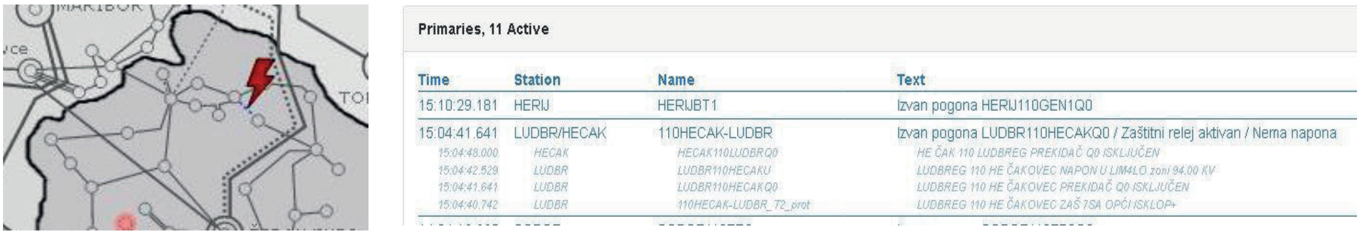
When the grouped event is expanded, the most important signals from the SCADA event lists are presented (breakers tripped, protection trip events, voltage limits).

The visual representation in the diagram in IAP is presented with the arrow pointing to the network element that was tripped, as shown in Figure 7.

CONCLUSION

IAP system in control room is powerful and useful tool during normal operation conditions and disturbances. Very efficient tool which output points out accurately and promptly on root cause transmission network element stressed with disturbances.

Although the main benefit of the IAP tool is to help the operator in detection of the root cause during cascading events, it can also be used to monitor the operational state during normal operation as well as for automated generation of outage reports. Due to the fact that such a grouping of information contains almost all relevant information (outage duration, protection trip or operator command) these lists can be used as an input for the operator diary as well as for different reporting purposes. Furthermore, the integration of such a tool with software for outage planning and software for weather and storm monitoring can be made, in order to detect the cause of the outage.



Primaries, 11 Active

Time	Station	Name	Text
15:10:29.181	HERIJ	HERIJBT1	Izvan pogona HERIJ110GEN1Q0
15:04:41.641	LUDBR/HECAK	110HECAK-LUDBR	Izvan pogona LUDBR110HECAKQ0 / Zaštitni relej aktivan / Nema napona
15:04:48.000	*HECAK*	*HECAK110LUDBRQ0*	*HE ČAK 110 LUDBREG PREKIDAČ Q0 ISKLJUČEN*
15:04:42.529	*LUDBR*	*LUDBR110HECAKU*	*LUDBREG 110 HE ČAKOVEC NAPON U LIM4LO zoni 94.00 KV*
15:04:41.641	*LUDBR*	*LUDBR110HECAKQ0*	*LUDBREG 110 HE ČAKOVEC PREKIDAČ Q0 ISKLJUČEN*
15:04:40.742	*LUDBR*	*110HECAK-LUDBR_T2_prot*	*LUDBREG 110 HE ČAKOVEC ZAŠ 7SA OPĆI ISKLOP+*

Figure 7. IAP presentation list for a simple protection trip event

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Development and Impact of Flow-Based Methodology in Core Region

SUMMARY

The Core Flow-Based Market Coupling Project (Core FB MC) focuses on the development and implementation of the day-ahead market activities in the Core Capacity Calculation Region (Core CCR) within the Single Day-Ahead Coupling (SDAC). The Transmission System Operators (TSO) and Nominated Electricity Market Operators (NEMO) of the Core CCR aim to introduce FB MC at the regional level and ultimately, to facilitate the merger of regional markets and the creation of a fully integrated European Internal Energy Market.

Flow-Based Market is currently deployed within the Single Day-Ahead Coupling across Central Western Europe (CWE) covering Austria, Belgium, France, Germany, Luxemburg and the Netherlands. Within the Core Flow-Based Market Coupling project, all borders of the Core CCR will be coupled based on the Flow-Based capacity calculation methodology developed in the framework of the Capacity Allocation and Congestion Management (CACM) Regulation. The Core CCR consists of the bidding zone borders between the following EU Member States` bidding zones: Austria, Belgium, Croatia, Czech Republic, France, Germany, Hungary, Luxembourg, the Netherlands, Poland, Romania, Slovakia and Slovenia.

The Flow-Based Methodology is a methodology in which physical network constraints are obtained based on the available constraints on the critical elements of the network (branch) and the power transmission allocation factors that are defined for each critical branch and each zone (Bidding Zone) within Core CCR. These factors describe how the position of each bidding zone changes when the energy flow in the critical branch changes. The computer algorithm then seeks an optimal exchange of energy between the bidding zones.

Compared to the existing Net Transmission Capacity (NTC) methodology, the FB methodology takes into account multiple parameters and optimization conditions and therefore better reflects the actual circumstances in the network. The methodology for calculating the flows of power derives from the Commission Regulation (EU) 2015/1222 on the Establishment of CACM regulation (Article 20) and represents an important part of the European Target Model. The methodology contributes to reducing the price differences between national electricity markets, which leads to more stable prices, and increases the social benefits of the involved countries.

This paper will provide historical overview of the Core FB MC project, which is based on the decision of the Agency for the Cooperation of Energy Regulators (ACER) on November 17th, 2016. It will further on provide a presentation of all the working groups and their tasks within the FB MC project, high-level architecture and information flows, a detailed description of test processes divided into separate test

Given that the project is still in the implementation phase, and that Croatia is part of it since 2016, article will look at the local perspective and expectation from the moment of realization of the project, but will as well give an overall progress picture of the energy market and energy trading for the entire Core region.

KEYWORDS

Core Flow-Based Market Coupling (Core FB MC), Flow-Based Methodology, Single Day-Ahead Coupling (SDAC), Nominated Electricity Market Operator (NEMO), Agency for the Cooperation of energy Regulators (ACER), Core capacity calculation region (Core CCR), Power exchange, Energy market, Energy trading.

HISTORICAL OVERVIEW

The FB MC was initiated in June 2007 in CWE region (including Belgium, France, Netherlands and German-Austrian- Luxembourgish bidding zone) with a Memorandum of Understanding between Energy Ministers, Transmission System Operators (TSOs), Power Exchanges (PXs), National Regulatory Authorities (NRAs), and Market Parties Platforms. After 8 years of developing FB methodology, it was successfully implemented in May 2015 by the transmission system operators (TSO). In June 2016 the Core capacity calculation regions (Core CCR) was created based on the ACER decision 06/2016 on the electricity TSOs proposal for the determination of Core CCRs. In September 2017 Flow-Based Capacity Calculation Methodology developed jointly by all Core CCR TSOs was submitted to regulatory authorities (NRAs) for adoption based on the Article 20 of CACM regulation. In April 2018 the methodology was returned with a request for amendment. Two months later the TSOs resubmitted the methodology. Eventually, the NRAs did not reach a unanimous decision. The methodology was escalated to ACER and in the final form published in February 2019. [3]

Martina Vajdić, Marko Kelava, Development and Impact of Flow-Based Methodology in Core Region, Journal of Energy, vol. 69 Number 4 (2020), p. 30–34, https://doi.org/10.37798/202069452

Project participants (TSOs and NEMOs) are listed in Table 1. [1]

Table 1. TSOs and NEMOs - project parties [1]

	AT	DE		SK	CZ	PL	HU	SI	HR	RO
TSO	APG	Tennet DE	50 Hertz	SEPS	CEPS	PSE	MAVIR	ELES	HOPS	Transe-lectrica
NEMO	EXAA/ EPEX/ EMCO	EXAA/ EPEX/ EMCO		OKTE	OTE	TGE/ EPEX/ EMCO	HUPX	BSP	CROPEX	OPCOM

In addition to the above participants, France, Germany, Belgium, Netherlands and Luxembourg have additional representatives (TSOs) in the project listed in Table 2. [1]

Table 2. TSOs - additional project parties [1]

	FR	DE		BE	NL	LU
TSO	RTE	Amprion	TransnetBW	Elia	Tennet NL	CREOS

Figure 1 shows a symbolic map of Europe with the market Core CCR countries.

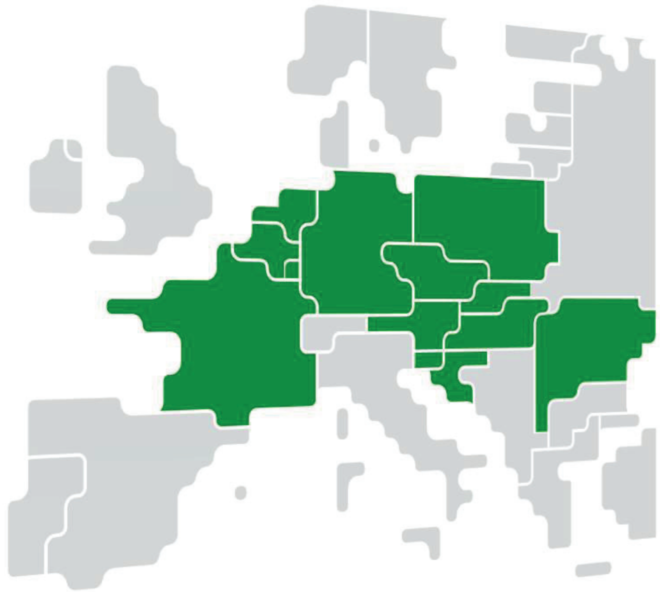


Figure 1. Core CCR

WORKING GROUPS

In order for the project to be realized, established are several working groups (WG) and task forces (TF), responsible for carrying out specific tasks. The list of the present working groups is provided in Figure 2.

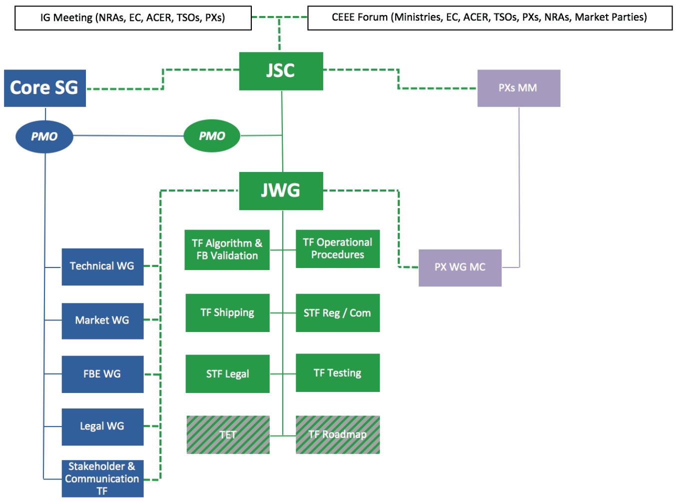


Figure 2. Core FB MC working groups

Joint Steering Committee (JSC) shall:

- Be responsible for signing off the most important deliverables and in case escalation is needed, they will be the decisional body
- Approve costs and budget
- Delegate tasks to Project bodies
- Supervise the progress of the Project (roadmap) and work of the Project bodies, in particular, JWG and PMO

Project Management Office (PMO) shall:

- Support JSC in organizational matters
- Support TF leaders in all preparation and coordination activities for the respective tasks. The PMO participates in all conference calls, draft meeting minutes and ensures the follow-up of issues and actions.

Joint Working group (JWG) shall:

- Ensure and organize the fulfilment of the tasks set by JSC
- Provide JSC with reports and decision proposals prepared by itself or the other Project bodies

TF Algorithm & FB Validation shall:

- Discuss and assess results of Internal Parallel Run that is provided by Core FB CC Project, Algorithm Smoke test and Acceptance test that will be provided by PCR, External Parallel Run, Member simulation testing and identify possible issues/risks during implementation
- Further evaluate performance of capacity calculation and allocation after Go-Live

TF Operational Procedures shall:

- Identification of the operational procedures needed for Core FB MC
- Translation of the Market Design for Implementation into respective processes and procedures
- Elaboration of respective documentation, i.e. Core FB MC Operational Procedures;
- Ensure compatibility between Core FB MC (including also TSO side result verification procedures if applied) and SDAC pre-coupling and post-coupling procedures while complying with Regulation (EU) 2015/1222
- Validate and if needed update all above listed sets of procedures after testing, if needed
- Update all above listed sets of procedures after NRAs review and approval, if needed
- Define rules for the Operational System Committee (OPSCOM) (related to pre- and post- coupling processes)

TF Shipping shall:

- Design the overall shipping and clearing solution for Core FB MC
- Design the implementation process for the shipping and clearing solution

Supportive TF Reg/Com shall:

- Draft Press Releases based on JWG MC request
- Elaborate a Communication Plan taking into consideration all necessary stakeholders information requirements, legal obligations and experience from comparable projects
- Plan and organize the workshops for external stakeholders
- Prepare market training documents together with other TFs and JWG and interact with the market participants and stakeholders
- Manage general communication with the market participants
- Draft answers for journalists when requested by JWG
- Provide project information for electronic platforms (i.e. website)

Supportive TF Legal shall:

- Design the overall contractual framework for Core FB MC
- Ensure compatibility of Core contractual framework with other relevant regional projects and CACM
- Design the schedule of the agreements delivery
- Draft the common contract(s)
- Participate in the legal check of the agreements
- Identify the necessary contractual framework for shipping and cross-border clearing in the Core region based on inputs of TF Shipping

TF Testing shall:

- Design of overall testing activities which should be divided into separate test phases (i.e. development of the Master Test Plan)
- Coordinate isolated system, integration, simulation, SDAC, member and acceptance tests
- Assess test results and prepare the test end report
- Prepare the approval of the technical and procedural readiness of project parties as a precondition for Core FB MC Go-live
- Align its activities and cooperate with TF Operational Procedures and
- TF Shipping

According to the above tasks, there are several important milestones to be finished before the Core Flow-Based Market Coupling goes live [3]:

- Market Design for Implementation - Document containing the description of the entire normal business process for coupling day-ahead markets including issues such as shipping arrangements, congestion income collection and aggregation, IT infrastructure and data communication (JWG; TF Shipping)
- Procedures design – normal, back-up, fallback, rollback, special and other procedures (TF Operational Procedures)
- Simulation and validation – tests performed in the test environment of the computational algorithm (TF Testing)
- External parallel run – real time testing by comparing the results of the current NTC calculation method and the FB method for the period of six months (TF Algorithm & FB Validation)
- External implementation - design, development and implementation of local IT systems of individual project parties
- Final market coupling testing – a lot of tests performed before go-live (TF Testing)

HIGH-LEVEL ARCHITECTURE AND INFORMATION FLOWS

The high-level process architecture for the normal operation of a flow-based day-ahead market coupling in the Core CCR, shown in Figure 3, includes required systems, as well as produced and exchanged information represented by arrows.

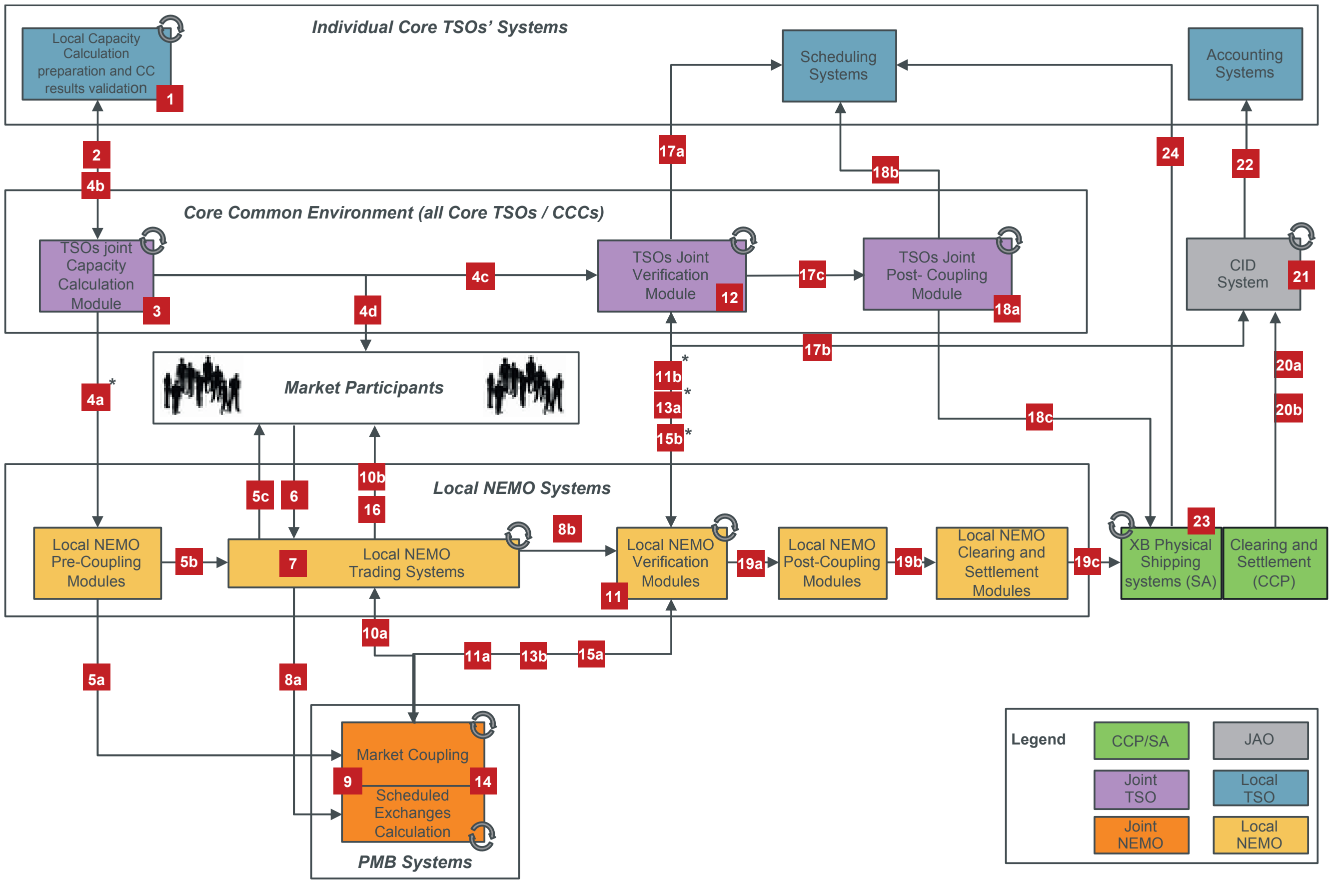


Figure 3. High-level process architecture

THE MARKET COUPLING PROCESS

The market coupling process is divided in three phases: Pre-Coupling, Coupling and Post-Coupling phase. The following subchapters briefly explain each of the phases.

PRE-COUPLING

For Pre-Coupling activities, the following tasks have to be managed:

- CDD calculation - TSOs are fully responsible for capacity data domain provision, verification, adjustment and approval of final CDD, as well as delivering them to NEMOs (Local NEMO Pre-Coupling Systems).
- Final CDD publication - TSOs are responsible for publication of final CDD on the ENTSO-E Publication Platform. NEMOs are responsible for publication of final CDD on Local NEMOs' Trading Platforms for local market participants.
- Collection of energy buy/sell orders and their processing - NEMOs are responsible for collecting and aggregation of market participants buy/sell energy orders. NEMOs deliver aggregated orders to PMBs. NEMOs are responsible for delivering final CDD to PMBs and Trading Systems.

COUPLING

Market coupling results containing at least but not limited to:

- a single clearing price for each bidding zone and market time unit in EUR/MWh and;
- a single net position for each bidding zone and each market time unit and;
- information which enables determination of an execution status of orders;
- scheduled exchanges;

Market coupling results are calculated by NEMOs via PMB Systems in accordance with the SDAC process and related procedures.

The Coupling is under the responsibility of NEMOs, however, the TSOs are responsible for providing the final confirmation of the results.

POST-COUPLING

The post-coupling activities consist of cross border physical shipping (Cross border scheduling), clearing and settlement of scheduled exchanges. Transfer of the energy from one bidding zone to another bidding zone, is performed by a designated institution(s) (same or a different designated institution) for cross-border scheduling and cross-border clearing and settlement. Congestion income is collected by designated institutions preforming cross-border clearing and settlement and transferred to the congestion income distributor (CID) and shared between concerned TSOs.

For post-coupling activities, the following cross-border relevant tasks have to be performed:

- Cross border scheduling, cross border clearing and settlement (physical and financial shipping);
- Sending of the congestion income to CID;
- Calculation and distribution of congestion income shares by CID (on multilateral basis between CID and TSOs).

Additionally, in case of some problems arising while performing normal market coupling processes, provided are two solutions depending on the nature of the problem itself.

FALLBACK SOLUTION

In case the day-ahead market coupling cannot be run with the normal timings and backup procedures do not solve the issue, it may be needed to proceed with different decoupling situations and to allocate respective cross border capacities via a fallback solution (applying fallback procedures).

ROLLBACK SOLUTION

During the first six weeks after the Core FB MC project go-live, if the TSOs and/or the NEMOs are facing regular serious problems, which cannot be solved within acceptable period, a Rollback Situation can be triggered to avoid persistent uncertainties for Market Participants. The Rollback will end with the resolution of the problems and the announcement of new Go-live by the Core FB MC project JSC.

HARMONIZATION OF PRINCIPLES AND CHARACTERISTICS

In accordance with the relevant methodologies developed under the CACM Regulation, it is necessary to harmonize the basic principles and characteristics of market coupling, described in table 3, among project participants.

Table 3. Comparison of SDAC and CORE FB MC [1]

Time zone	CET/CEST	
Implemented countries	SDAC	Core CCR
Type of coupling	ATC based MC	FB based MC
Providing the Capacities to NEMOs	10:20	10:30
Standard Publication of Capacities	10:30	10:30
Orderbook DA Market Gate Closure Time of NEMOs	12:00	12:00
Standard Publication of preliminary Results by NEMOs	12:42	12:42
Standard Publication of Final Results by NEMOs and TSOs	12:56	12:55 for NEMOs After 12:55 for TSOs
Nomination Deadline (XB)	14:30	14:301
Cross-border Flow decimals [MWh]		One digit
Price step of Market clearing price [€/MWh]		Two digits
Min/Max prices [€/MWh]		-500/+3000
Second Auction Trigger [€/MWh]		-150/+1500 where applicable
Volume Tick size of bids [MWh]		One digit
Price step for bids [€/MWh]		Two digits

TEST PROCESSES

The implementation phase of the Core Flow-Based Market Coupling project comprises a joint testing period with all involved parties which can be divided in the seven phases: Isolated System Test, Pre-Integration Test (Pre-FIT), Full Integration Test (FIT), Simulation Test, Single Day-Ahead Coupling (SDAC) Simulation Test, Member Test and Acceptance Test. [2]

Characteristics of these tests are [2]:

- Isolated System Test demonstrates that all individual systems under responsibility of individual Parties are ready for further connected testing.
- The Pre-FIT Test demonstrates that communication between the Flow-based systems involved meets the infrastructure requirements and that the used files are compatible and can be exchanged. In addition, the performance of a Normal day is one of the aims of this phase.
- The FIT test demonstrates that communication between the involved systems meets the functional requirements to support the FB MC process. Both Normal days, as well as Backups and special scenarios, are part of the test that will be performed during this phase.
- The Simulation Test finally demonstrates that the common and local procedures fit the purpose they are developed for; the developed systems meet the functional and quality requirements and the local

and common procedures.

- The SDAC Simulation Test demonstrates the Simulation test with SDAC project parties.
- Member Test demonstrates the FB MC daily trading process to the market participants.
- Acceptance Test demonstrates that there are no defaults that prevent the GO-live.

The Testing TF proposes to the JWG, who further distributes it to the JSC as decision body, to accept the solution if all scenarios and levels are successfully performed and all known issues are registered and acceptable for all parties involved. [2] Figure 4 shows the organization of Testing TF.

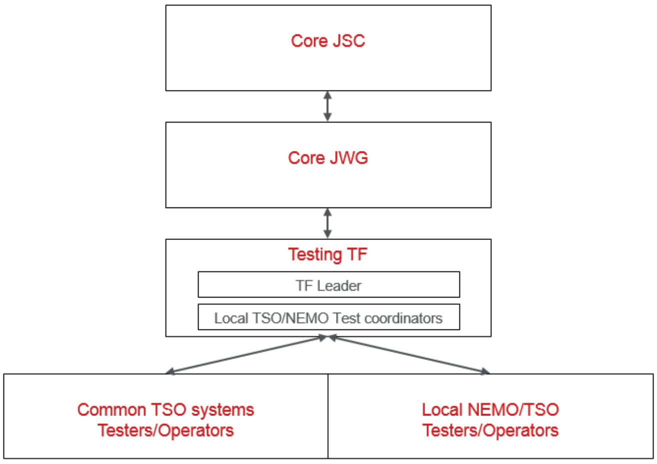


Figure 4. Testing TF organization [2]

During FIT and SIT phase there are several systems needed depending on the part of the market coupling process. These systems are listed in Figure 5.

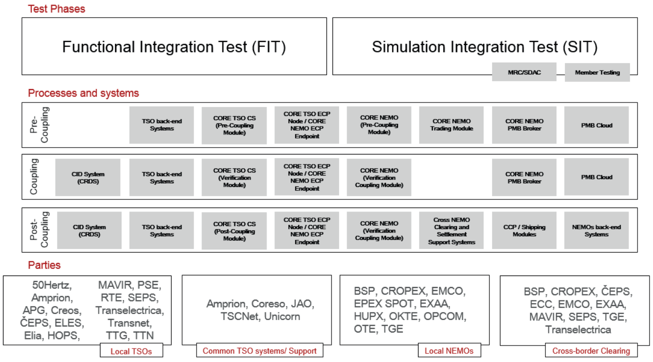
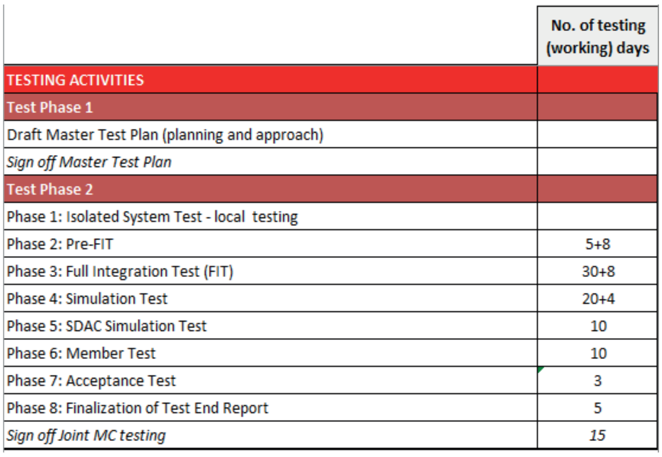


Figure 5. Required systems during testing [2]

Testing phases and their approximate duration are described in Figure 6. At the time of writing this article, the Test Phase 2 was, due to unforeseen delays, postponed for a few months. Test Phase 1 was finalized in Q4 2019.



	No. of testing (working) days
TESTING ACTIVITIES	
Test Phase 1	
Draft Master Test Plan (planning and approach)	
Sign off Master Test Plan	
Test Phase 2	
Phase 1: Isolated System Test - local testing	
Phase 2: Pre-FIT	5+8
Phase 3: Full Integration Test (FIT)	30+8
Phase 4: Simulation Test	20+4
Phase 5: SDAC Simulation Test	10
Phase 6: Member Test	10
Phase 7: Acceptance Test	3
Phase 8: Finalization of Test End Report	5
Sign off Joint MC testing	*15*

Figure 6. Test planning [2]

CONCLUSION

The overall common goal of the project is to successfully launch the Core FB MC in line with CACM Regulation. The implementation of the FB methodology in practice will optimize the allocation of available trading capacity, which in market integration optimizes the efficiency of energy trading by allocating cross-border transmission capacities between coupled day-ahead markets, taking into account the physical constraint of the network in a more precise and detailed manner (variable production from RES). In FB MC, the allocation of transmission capacity is partly done simultaneously with the market clearing, unlike NTC/ATC where the allocation of transmission capacity is done ex-ante the market clearing. As such, more transmission capacity is made available to the market in FB MC. This is confirmed by off-line test runs of the FB MC, which indicate an increase in social welfare due to more transmission capacity, compared to NTC/ATC. It also reduces price difference between the national electricity markets (prices are more stable). Given that Croatia is part of the FB MC project since 2016, it is expected, that after its implementation, a utilization of cross border capacity will be higher, which will consequently lead to the higher volume on CROPEX, while maintaining the required level of the network security by more efficient congestion management.

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FOOTNOTES

[1] The deadline 14:30 applies If the MC results are available between 12:56 and 13:20. If the MC results are available after 13:20, the deadline is postponed to 15:30

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