REAL-TIME DYNAMIC SIMULATION OF A POWER SYSTEM RESTORATION PROCESS

Master thesis in Electrical Engineering

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DINAMIČNA SIMULACIJA PROCESA PONOVNE VZPOSTAVITVE ELEKTROENERGETSKEGA SISTEMA V REALNEM ČASU

Magistrsko delo

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<tbody>
<tr>
<td>EPS</td>
<td>Electric power system</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission system operator</td>
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<tr>
<td>ENTSO-E</td>
<td>European Network of Transmission System Operators</td>
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<tr>
<td>UFLS</td>
<td>Under-frequency load shedding</td>
</tr>
<tr>
<td>TOV</td>
<td>Transient overvoltage</td>
</tr>
<tr>
<td>RTDS</td>
<td>Real-Time Digital Simulator</td>
</tr>
<tr>
<td>EMT</td>
<td>Electromagnetic transient</td>
</tr>
<tr>
<td>AVR</td>
<td>Automatic voltage regulator</td>
</tr>
<tr>
<td>SG</td>
<td>Synchronous generator</td>
</tr>
<tr>
<td>p.u.</td>
<td>Per unit</td>
</tr>
<tr>
<td>CB</td>
<td>Circuit breaker</td>
</tr>
<tr>
<td>TR</td>
<td>Transformer</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>HIL</td>
<td>Hardware-In-the-Loop</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional-Integral</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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Abstract

After a total blackout in its own area, each Transmission System Operator (TSO) has a responsibility to initiate a restoration process as quickly, safely and reliably as possible, re-establishing the integrity of the electric power system (EPS). In recent years, this became a topic on which the European Network of Transmission System Operators (ENTSO-E) increased attention, requiring each TSO to establish and test appropriate restoration scenarios. In order to be able to restore the EPS safely and efficiently, it is necessary to verify the feasibility of a restoration scenario and be aware of the main issues during such a procedure. It is therefore important to develop testing models that should be able to simulate the behaviour of the EPS under various conditions.

This master thesis presents a real-time dynamic simulation of an EPS restoration procedure. In general, the thesis is split in two main parts. In the first part, an EPS is modelled for several restoration scenarios, implementing different re-energization approaches. We considered several scenarios for the dynamic analysis, applying re-energization of the transmission system by black-start units or, with the help of neighbouring systems. In the second part of the thesis we focused on the operation of the re-energized areas, in terms of synchronizing the re-energized parts of the EPS, adding load to the system and maintaining the frequency.

The simulations were carried out by specially designed computer system with a custom hardware and all-in-one software, Real Time Digital Simulator (RTDS). Using the RTDS device for restoration processes enables a wide range of simulations under various operating conditions, furthermore a possibility of testing a real physical power equipment operation during a black-start procedure.

**Key words:** black-start, dynamic phenomena, power system restoration, RTDS, real-time simulation
Povzetek

Po celotnem razpadu elektroenergetskega sistema (EES), je vsak sistemski operater prenosnega omrežja odgovoren zagotoviti ponovno vzpostavitev sistema čim hitreje, varno in zanesljivo. V zadnjih letih je v okviru ENTSO-E postalo aktualna tema, in se posledično od vsakega operaterja prenosnih sistemov zahteva, da vzpostavi ustrezne scenarije vzpostavitve omrežja. Za varno in učinkovito ponovno vzpostavitev EES je potrebno preveriti izvedljivost teh scenarijev in se zavedati glavnih izzivov med izvajanjem postopka. Zato je pomembno razviti testne modele, s pomočjo katerih je mogoče simulirati obnašanje modela EES v različnih pogojih.

Magistrska naloga predstavlja postopek izvajanja dinamičnih simulacij vzpostavitve EES v realnem času. V splošnem je naloga razdeljena na dva glavna dela. V prvem delu je električni sistem zasnovan za dva različna pristopa vzpostavljanja napajanja, in sicer od spodaj-navzdol in od zgoraj-navzdol. Po načelu vzpostavitve od zgoraj-navzdol se EES ponovno vzpostavi s pomočjo sosednjih EES. Pomanjkljivost takšnega pristopa se pojavi v primeru razpada na širšem območju, v katerega so lahko zajeti tudi sosednji EES. Posledično električna napetost na povezovalnih vodih s sosednjimi EES morda/najverjetneje ni na voljo. V tem primeru se mora vzpostavitev začeti s strani lastnih proizvodnih enot ki imajo možnost zagona brez zunanjega napajanja v primeru, pri čemer se predpostavi da je znotraj izoliranega območja vsaj ena elektrarna s sposobnostjo zagona brez zunanjega napajanja. Posledično električna napetost na vložnih vodih je morda/najverjetneje ni na voljo. V tem primeru se mora energijo vložiti pri pokritju lastnih proizvodnih enot in obseg pri prenosu napetosti na vložnih vodih je morda/najverjetneje ni na voljo. V tem primeru se mora energijo vložiti pri pokritju lastnih proizvodnih enot in obseg pri prenosu napetosti na vložnih vodih je morda/najverjetneje ni na voljo. V tem primeru se mora energijo vložiti pri pokritju lastnih proizvodnih enot in obseg pri prenosu napetosti na vložnih vodih je morda/najverjetneje ni na voljo. V tem primeru se mora energijo vložiti pri pokritju lastnih proizvodnih enot in obseg pri prenosu napetosti na vložnih vodih je morda/najverjetneje ni na voljo. V tem primeru se mora energijo vložiti pri pokritju lastnih proizvodnih enot in obseg pri prenosu napetosti na vložnih vodih je morda/najverjetneje ni na voljo. V tem primeru se mora energijo vložiti pri pokritju lastnih proizvodnih enot in obseg pri prenosu napetosti na vložnih vodih je morda/najverjetneje ni na voljo. 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postopek zaporednega vklapljanja elementov ter ii) mehki zagon. Sprva je bila izvedena simulacija sekvenčne metode vklapljanja elementov. Pri vklopu posameznega transformatorja na izmenični vir napetosti pride do znanega dinamičnega vklopnega pojava, ki ima za posledico magnetilni tok transformatorja z visoko amplitudo. Prehodni pojav je odvisni od trenutka priklopa transformatorskih navitij in količine remanentnega fluksa v jedru. Remanentni fluks je stohastičnega značaja in ga zato ni mogoče zanesljivo predvideti. Precej verjetno pa je, da bo transformator imel določeno stopnjo remanentnega fluksa, saj je bil pred izpadom v obratovanju. Prisotnost remanentnega fluksa deluje kot odmik, ki lahko privede transformator v globlje nasičenje med prihajajočim vklopm. Poleg tega običajno v praksi prihaja do situacij, ko ob vklopu v električni bližini že obratujejo nekateri drugi transformatorji. Transformator, ki se priklučuje, je lahko povezan bodisi vzporedno bodisi zaporedno s temi transformatorji. Rezultati simulacij so pokazali, da lahko zato poleg že znanega vklopnega pojava transformatorja, pride tudi do interakcij med večjimi transformatorji. Te so znane kot simpatetični vklopni pojav. Da bi se tako prenapetostim kot tudi vklopnim tokom izgonili, je v nadaljevanju opisana tudi metoda mehkega zagona iz brez-napotostnega stanja. Tudi ta postopek smo s simulacijami uspešno ponazorili. Generator smo sprva iz mirovanja za gnavili do njegove nazivne hitrosti. Zatem, ko je bila dosežena nazivna frekvenca (konkretno 50 Hz), smo preko vzbuivanja rotorskega navitja napetost v omrežju postopoma dvignili do nazivne vrednosti. Rezultati so potrdili, da je tako mogoče začeti vzpostavljanje napetosti na 400 kV omrežju tudi z manjšimi agregati, in sicer brez težav s priključevanjem večjih transformatorjev.

V drugem delu magistrske naloge smo se osredotočili na povezovanje več ločeno vzpostavljenih otokov, in sicer v smislu sinhronizacije otokov, dodajanja obremenitve v sistem in vzdrževanja stabilne frekvence. Pri tem je posebej izpostavljeno vzdrževanje frekvence, saj so generatorji v otočnem obratovanju. Najprej smo izdelali model EES z dvema generatorjema, da bi prikazali delovanje dveh posameznih tipov turbinskih regulatorjev: i) ko sta turbinska regulatorja nastavljena na regulacijo po statiki in ii) ko je en regulator nastavljen na regulacijo frekvenca drugi pa na regulacijo po statiki. V nadaljevanju smo po uspešnem zagonu dveh ločenih otokov simulirali tudi njuno sinhronizacijo, ki smo ga uporabili tudi kot sredstvo za predstavitev uporabniškega vmesnika simulatorja. Vmesnik omogoča izvedbo tako konvencionalnega sekvenčnega priključevanja elementov kot tudi mehkega zagona, različne možnosti nastavitev delovanja turbinskih regulatorjev, sinhronizacije ter dodajanje odjema.

Vse simulacije v nalogi smo izvedli z digitalnim simulatorjem za izračune v realnem času (RTDS). Uporaba RTDS naprave omogoča široko paleto simulacij v različnih delovnih
pogojih, poleg tega pa tudi možnost preizkušanja dejanske fizične opreme med postopkom ponovne vzpostavitve EES. S tega stališča smatramo izdelano orodje kot dober pripomoček za preverjanje izvedljivosti zagona konkretnega EES iz brez-napetostnega stanja, pa tudi kot trening za operaterje, ki bo v prihodnje nadgrajen z implementacijo zaščitne opreme.

**Ključne besede:** ponovna vzpostavitev elektroenergetskega sistema, zagon iz brez-napetostnega stanja, dinamični pojavi, RTDS, digitalna simulacija v realnem času
Chapter 1

1.1. Introduction

The electrical power system (EPS) is the largest system ever created and controlled by man. Since our modern lifestyle has become strongly dependent on continuous electric power supply, it is essential to maintain reliable operation of the EPS. In general, EPS in developed countries exhibit a high degree of reliability owing to the well-established standards and criteria for the design, planning, construction and operation of the EPS, moreover to the interconnections with the neighbouring EPS. However, the EPS is becoming more complex with the incorporation of new smart technologies and digitalization. Moreover, the classical EPS operation paradigm is changing rapidly with less traditional power plants operating and a massive increase in distributed renewable generation, leading to often drastically changed operating conditions. New challenges arise with the extension of the EPS by creating interconnections between neighbouring countries. Furthermore, with deregulation of the system and implementation of the energy market, power flows are determined by competitive energy markets, which brings additional challenges in its operation. These significant changes in the energy sector provide multiple benefits, but on the other hand, increase the vulnerability of the existing power infrastructure as the system operates close to its stability margins. Consequently, even small disturbance may cause instability, leading to disturbed operating conditions. In some cases, major interruptions occur due to various causes such as natural disasters, equipment failure, protection relay malfunctioning or human errors. A single disturbance may initiate cascading failures causing emergency operating conditions [4]. In case of extreme contingencies, simultaneous power outages lead to partial blackouts, furthermore the EPS may experience wide-spread blackouts or total system collapse, which represents the most extreme failure in the interconnected EPS.

Despite the fact that large-scale blackouts are rare events, they have enormous consequences on society and economy. Restoring the EPS is of prime importance to minimise these consequences. A pivotal role for a successful restoration of the EPS strongly depends on the preparedness of the transmission system operators (TSOs) for such an event. Plans to restore the EPS after a major blackout, and a consequential re-synchronization, are being prepared in
advance, in order to achieve the efficient establishment of normal operation of the EPS as soon as possible. This includes operator’s training and verification of the proposed scenarios. In recent years, this became topic on which the European Network of Transmission System Operators (ENTSO-E) increased attention, requiring each TSO to establish appropriate restoration scenarios. The European Commission Regulation 2017/2196 [2] imposes that each TSO has to design and verify an adequate restoration plan for its own control area.

1.2. Motivation

In the recent past, the number of major incidents in the EPS made the TSOs to be aware of the necessity to prepare restoration plans, prove their viability and keep them updated. The restoration plans go through a few steps before the implementation: design, testing, verification and eventually activation. The first phase includes number of studies and investigations for initiating possible black-start scenarios. In the development of the restoration plan, TSOs shall perform further studies based on simulations, to verify the feasibility of a black-start scenario and be aware of the main issues during such a procedure, before real tests are attended. The challenge is to filter out technically viable scenarios from a number of possible ones. Besides the evaluation of the restoration strategies, the knowledge and experience of the operators is of a great importance when implementing a restoration plan following a widespread blackout in the actual system. Considering that such events are not common, experience is gained through simulation sessions representing realistic scenarios, when operators are allowed to schedule and implement different manoeuvres on numerus possible system conditions that can happen upon. In the context of the practices in Europe on emergency and restoration the Network code [2] clearly states that in ENTSO-E, all TSOs have to regularly evaluate their restoration plans. Specifically in the Baltic, the Continental Europe, the Great Britain, the Ireland/Northern Ireland and the Nordic areas, restoration plans are evaluated by simulations or off-line calculations.

As EPS restoration is attracting more attention recently, it is important to provide insight into the basic principles of restoration procedure and the issues related with the underlying processes. This master thesis analyses the EPS restoration process based on real-time simulations. The thesis discusses different approaches that are implemented in EPS restoration. A particular focus is given on the dynamic behaviour of the system as a result of different
actions taken regarding to the re-energization of the system. These actions refer to the energization of transmission line and transformers, furthermore synchronization of generating units and restoration of load. Fast transients occur due to the switching manoeuvres, which can possibly be a cause for unsuccessful restoration and prolongation of the procedure. Therefore, it is important to identify possible problems, which eventually aids the system planning decisions. To analyse the dynamic phenomena the simulations are carried out by specially designed computer system with a custom hardware and all-in-one software, Real Time Digital Simulator (RTDS).

Several studies ([10], [11], [12]) give a comprehensive review of the EPS restoration issues and the complexity of the process in terms of the EPS dynamics. Previous studies in this field include analysis of the transient over-voltages during a system restoration [14], as well as assessment of the temporary over-voltages and transients during transformer’s energization after an EPS collapse ([15], [16], [20]). However, most of the simulations are carried out using offline tools such as Netomac, MATLAB/Simulink, ATP and Power factory DlgSILENT. The contribution of this thesis is the use of the RTDS – a state-of-the-art in digital simulation. The simulator allows connection of a physical devices for hardware-in-the-loop (HIL) testing. Therefore, protection and control equipment can be connected to the simulator and tested, which is an advantage over other simulation tools since our future plans include inclusion of real equipment as well. Ref. [13] presents the use of the RTDS for a HIL testing of a relay in a black-start plan.

Having all this in mind, the advantage of modelling EPS restoration scenarios using the RTDS, for training and testing purposes, is obvious.

1.3. Thesis organisation

The thesis consists of six chapters. Apart from Chapter 1 that gives introduction to the topic, the remainder of the thesis is structured as follows.

In Chapter 2 taking the ENTSO-E Policy 5 [1] as a starting point, the basic definitions of the terms are given, explaining the operating states of the EPS. Furthermore, the past major blackouts worldwide are reviewed highlighting the causes behind the blackouts and their
consequences. Chapter 2 introduces the process of an EPS black-start and is concluded with international experiences in EPS restoration.

Chapter 3 briefly describes the components used for modelling of the testing models, furthermore it gives insight into the dynamic phenomena related with the components and the restoration process.

In Chapter 4 two main black-start approaches are presented. Applying different configuration of EPS models, the results from the simulations are analysed and evaluated.

Chapter 5 describes the synchronization procedure and evaluates the parallel operation of generating units once they are synchronized. Moreover, it presents the operation of the black-start simulator.

The last Chapter 6 provides conclusion of the thesis and further work recommendations.
Chapter 2

Before introducing the EPS operating states, some basic definitions of the terms that are commonly used are given in continuation.

According to ENTSO-E’s Network code on operational security [3], **contingency** is defined as identified and possible or already occurred fault of an element, including not only transmission system elements, but also significant grid users and distribution network elements if relevant for the EPS security.

**Operational security** is the EPS capability to retain a normal operating state or to return to a normal operating state as soon and as possible, and is characterized by the satisfaction of thermal limits, voltage constraints, frequency limits and stability limits [3].

**Remedial action**, be it preventive or corrective control action, is defined as any measure applied by a TSO in order to maintain operational security [3].

**Cranking path** is a transmission corridor of the EPS, that provides electrical power from a power source, specifically a black-start generation unit to the targeted facilities needing external power source [12].

2.1. Operating states of the electrical power system

In order to understand the establishment of the EPS after a total or partial blackout, a prior understanding of the operating conditions of the EPS is required. Depending on its operating point, the EPS can be found in one of the predefined states, illustrated in *Figure 2.1*. According to ENTSO-E, EPS operating states classification given in [1] - is as follows:

- **Normal state**: in this state the EPS is within operational security limits in the N-situation after the occurrence of any contingency from the contingency list, whether it be a loss of a transmission line, transformer, or generator, taking into account the effect of the available remedial actions.
- **Alert state**: in this state the EPS is within operational security limits, but a contingency from the contingency list has been detected, and in case of its occurrence, it will violate
at least one security constraint. It indicates that the EPS is vulnerable to failures and the available preventive actions are not sufficient to keep the normal state.

- **Emergency state**: it is a state in which one or more operational security limits are violated, requiring for immediate implementation of corrective control actions in order to mitigate the risk of cascading failures.
- **Blackout state**: EPS state in which the operation of a part, or all of the transmission system is terminated.
- **Restoration state**: system state in which the objective of all activities taken by the TSO is to re-establish the system operation and maintain operational security after the blackout state or the emergency state.

As it is depicted in *Figure 2.1*, the EPS which is initially in normal operating condition, after being subjected to a disturbance is found in new operating state, depending on the severity of the contingency. The system enters in alert state in case of a less severe contingency, when the operating system variables vary from their rated values, but still they are within an acceptable range. By implementing a preventive control the system can be brought again in normal operating state. Also, it is possible that the contingency continues to increase which means that the system enters in emergency state. In case of a significantly severe disturbance occurring
during normal operating state, the EPS is also brought to an emergency state. Corrective control actions can possibly bring the system either in alert or normal operating state. However, if the contingencies continue to increase and the remedial action was ineffective or unavailable, the EPS enters in extremis state – system collapse or, blackout. When this happens, restoration is activated to re-establish the EPS operation.

The classification of the system states and possible transitions between them are carried out in relation to the degree of threat, or the urgency to prevent spreading the disturbance beyond the boundaries of the control area. The operational security limits are determined by each individual TSO, for each element in its transmission system according to the Network code [2], taking into account:

- voltage limits;
- short-circuit current limits;
- power-flow limitations in terms of thermal capacity ratings and permitted overloads.

2.2. Overview of the past major blackouts worldwide

In the event of a disturbance or failure in the EPS, it is essential that the EPS is able to maintain stable operation and to ensure continuous supply of electrical power to the customers. Although TSOs work to enhance EPS reliability, disturbances with more or less severe consequences still occur. When a major blackout occurs, the consequences can be devastating and far-reaching, affecting the social life of millions of people and resulting with huge economic losses. Such catastrophic failures happen as a consequence of cascading failures. Initial events that cause cascading outages and eventually EPS blackout, can be different, such as transmission line tripping or overloading, control and protection systems mal-operation, lightning strikes on EPS equipment, voltage collapse, human error, equipment failure, poor maintenance, and others ([12], [22]).

This subsection introduces a comprehensive overview of the past major incidents and cascading events that have occurred in the last several decades around the world. In addition, it highlights the root causes of the blackouts.
Blackout in Northeast United States – Canadian system on 14 August 2003

The initial event was tripping of a transmission line caused by a short-circuit failure. However, problems with voltage stability and reactive power flows were reported previously due to lack of investments in the grid [25]. A major impact on the event had the lack of communication between the operators and the unawareness of the upcoming risk in general. The cascading events continued as a result of wrong protection relay operation, leading to a ‘point of no return’ as stated in [25]. The final event led to a voltage collapse and outage of many generating units, resulting with a severe blackout. According to [22], more than 400 transmission lines and 531 generating units at 261 power plants tripped. At least 50 million people were affected.

Blackout in Italy on 28 September 2003

Italy imports large amounts of electrical power. On 28th September 2003, before the event took place, 6650 MW were imported from other countries, which was almost 26% of the Italian load [32]. The corridors from Switzerland were importing well above the day-before scheduled level. However, some events occurred, which ended with separation of the Italian EPS from the interconnected system and its collapse. The blackout was initiated by tripping of the interconnection line between Italy and Switzerland due to a tree flashover ([22], [32]). The reclosure was blocked due to a large voltage phase angle difference across the breaker, which led to overloading of the other transmission lines [32]. After a while, another interconnection tripped because of overloading. As the tripping continued, the Italian EPS lost synchronism and separated from the other systems. After that, the frequency started to decay which activated under-frequency load shedding (UFLS). Despite the UFLS action, the frequency continued to decay. In order to prevent inappropriate operation of the generation units, the under-frequency protection relays tripped several large generation units even before reaching the low threshold of 47.5 Hz [33]. All together with the other generating units, this resulted with 7500 MW production loss [32]. Unfortunately, UFLS was not able to avoid the blackout.

Blackout in India on 30 July 2012

In this event, there was a high power demand because of extreme weather conditions and on the other hand, the hydro power plants were generating bellow full capacity due to limited water supplies. This caused transmission line overloading. The first event was a circuit breaker
trip, which progressed with cascading failures and eventually led to a system collapse. This is the largest blackout in terms of lost power and affected people.

**Blackout in South Australia on 28 September 2016**

The cause for the cascading events was a storm damage to transmission line towers ([12], [22]). It is also noted that before the blackout occurred, there was a large amount of energy generated by non-synchronous generation (wind generation) in comparison to the conventional synchronous generation.

**Blackouts in Brazil (November 2009, February 2011 and March 2018)**

A last partial blackout was caused by a failure of a transmission line affecting more than 10 million people. Previously, the Brazilian grid experienced blackouts in 2009, then in 2011 too; the latter one caused by a transmission line failure, affecting 53 million people as surveyed in [22]. It was noticed from previous blackouts, that the system needs enhancement against disturbances.

According to the study report in [12], it is reasonable to highlight that one of the lessons learnt from previous experiences with blackouts and restoration processes is that there was a lack of verification of the black-start capability and cranking paths.

**Recent power outages in London, United Kingdom (9 August 2019)**

Recently, some power supply interruptions occurred in London, United Kingdom. Namely, on 9th August 2019, a series of events caused power outages in parts of London, affecting approximately 1 million customers. As reported in [34], following a lightning strike, an offshore wind power plant reduced its power supply by 737 MW and at the same time a steam turbine tripped reducing the production by 244 MW. These events which were not expected, caused rapid frequency decay and the under-frequency protection tripped more generation units. All the available power reserves were activated, however, there was a further tripping of generation units. UFLS was then activated which automatically disconnected customers, an action which successfully enabled recovery of the frequency and prevented the majority of the EPS from a blackout.
2.3. Restoration process

In case of a blackout state in the EPS, the re-energization process is to be implemented in order to re-establish the normal operation of the EPS. If larger geographic area is involved, the process requires more complex procedures. The related restoration process for re-energization is based on two main principles, namely top-down and bottom-up restoration ([1], [12]).

Applying the top-down restoration principle, the EPS is restored with assistance from neighbouring power grids. By this principle, the system is re-energized from the highest (top) transmission voltage level down to the distribution voltage level. Interconnection lines from the neighbouring EPS are energized to establish one or more cranking paths in order to re-energize the transmission network system. Generally, this process is relatively straightforward. However, in case of a wide spread blackout where the neighbouring systems may be involved too, the help from external EPS may not be available. After a wide-area EPS blackout, each TSO has a responsibility to initiate a black-start process independently, without relying on neighbouring countries. In this case, the system restoration must begin from pre-selected generating units with the ability for self-starting without an external power source. These units are called black-start units and the principle is known as bottom-up system restoration. It is the basis for restoration plans, since it is the only available method for restoration after a total system collapse and no assistance from the neighbouring EPS. By way of bottom-up restoration strategy, the restoration begins from lower (bottom) voltage levels up to higher voltage levels. Smaller black-start units are utilized to energize paths to supply power to larger generating units that are not capable to start-up themselves. Typically, small power plants such as hydro or gas power plants are suitable for self-starting by its own local stand-alone supply sources. This approach includes some basic steps: selection of generating units available for black-start, their start-up and stabilization of operation; restoration of transmission paths by energizing lines and transformers; expanding island(s) by connecting loads, then synchronizing island(s) in the appropriate time. There are various ways of implementing the re-energization process. Regarding to the formation of electrical islands there are three main possibilities ([26], [27]):

1. multiple islands – multiple small areas are being re-energized independently and then synchronized;
2. core island – one large more stable island is being formed;
3. backbone island – restoration to the auxiliary power of large generation units which are then used as backbone in the process of restoration.

Creating multiple islands restrains the impact of a failure during the process in some of the islands on affecting the other islands. In addition, it allows connection of critical loads in wider geographic areas. On the other hand, due to less inertia in the separate small islands, the islands are less stable and prone to frequency deviations. Difficulties may appear in the process of synchronization between islands [26]. With the core island method the re-energization starts with one black-start generating unit which energizes transmission cranking paths to priority loads and additional generators are synchronized progressively. An example for the Slovenian EPS would be building a core island from the thermal power plant (TPP) Šoštanj. Disadvantage of this method is that if a failure occurs during the restoration, the whole process must be restarted. Additionally, some of the priority loads may be far away from the core island. The backbone island restoration typically considers larger generators and higher nominal voltages [27]. In this way, a backbone island is formed to which smaller electric islands can subsequently synchronize. The larger generation capacity can provide transient stability, but there is a possibility of high over-voltages, which requires additional voltage control. Choosing the most appropriate method depends on the actual conditions in the system.

As for the switching strategies related to the bottom-up approach, there are mainly two possibilities: i) sequential switching of each element or, ii) the so-called soft energization method. For the sequential switching method, all circuit breakers are opened prior to re-energization process. During the re-energization, circuit breakers are being closed sequentially, energizing element by element in the grid. At the initial point of the restoration process, the part of the EPS, which is being re-energized, will be relatively weak with high equivalent system impedances because the process starts from small generators, or generally the number of generators that are on-line is small. Therefore, one of the challenges in the process is the energization of unloaded transformers. Problems may appear due to switching the power transformer that has higher rating in comparison to the local generator. The result may be malfunction of protection relays and risk failure of the procedure of black-start [9]. To reduce the risk of transient phenomena, the so-called soft energization method is being applied. In this case, all the components of the grid that is being re-energized are firstly connected to each other, and then the voltage is increased gradually [20]. Recently, some TSOs are testing the alternative method for re-energization of the network after a blackout ([28], [29], [30]).
In some cases, depending on the actual situation, a combination of both approaches, top-down and bottom-up, may be possible. TSOs can then choose hybrid approach to restoration using the assistance of neighbouring TSOs, as well as black-start generating units in its own control area, as the best solution to the conditions [12].

In order to be able to restore the EPS safely and efficiently, it is necessary to verify the feasibility of a black-start scenario and be aware of the main issues during such a procedure.

First, it is essential to have black-start generating units. As it was mentioned before, the black-start generating units must be capable to start operation from a completely de-energized state without access to external power supply. From the perspective of suitability, the flexibility of a power plant is important in order to quickly vary its power output to match the changing system demands in the early phase of the restoration process. In relation to this, the ability of the generation unit to tolerate frequency deviations in terms of continuing the operation plays a major role. The power plants which provide black-start services must go through restoration tests under realistic conditions in order to prove that the plant is able to provide the service ([2], [12]). These tests are supposed to be taken regularly on a yearly basis. The main aim is to create an electrical island with the black-start unit and test the running of the unit in islanded environment according to the bottom-up approach. Next step is re-synchronization of the power plant with the main grid.

Besides the generation unit start-up, critical aspects in the initial phase of system restoration process include re-energization of transmission lines and transformers. Due to a weak grid during black-start process and the non-linear characteristics of the transformers that are involved, there is a risk of various over-voltage stresses to appear when energizing transmission lines and unloaded transformers. In this circumstance, resonance can occur that results in high over-voltages. Some of the over-voltages last longer and some have a short duration. Switching surges are type of transient over-voltages that have high frequency components (100 Hz to 10 kHz) that decay within milliseconds. Their waveforms usually contain one, or just few, predominant voltage peaks. Temporary over-voltages are another type of transient over-voltages, which are of longer duration, from 50 milliseconds to seconds, and may have multiple high magnitude peaks. These over-voltages may be harmful to the components of the grid.

Eventually, the main concern in a black-start process is to keep frequency and voltage within acceptable limits. Especially the control of frequency is an important issue since the generator is in islanded operation. This is a challenge when it comes to synchronization of separate parts
of the system that have been re-energized. The majority of the load can be restored after the energization of larger units in the system.

2.4. International experiences in restoration processes

In this subsection, several approaches used in the restoration processes and experiences from the past events are briefly described (see Table 1).

<table>
<thead>
<tr>
<th>Country</th>
<th>Approach</th>
<th>Top-down restoration</th>
<th>Bottom-up restoration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>Hybrid</td>
<td>AC interconnections from bordering states</td>
<td>Hydro + pumped storage + gas turbines</td>
</tr>
<tr>
<td>Brazil</td>
<td>Hybrid</td>
<td>LCC HVDC + AC interconnections</td>
<td>Hydro</td>
</tr>
<tr>
<td>India</td>
<td>Hybrid</td>
<td>AC interconnections from bordering states</td>
<td>Hydro + gas turbines</td>
</tr>
<tr>
<td>Ireland</td>
<td>Hybrid</td>
<td>VSC HVDC + AC interconnections</td>
<td>Hydro + pumped storage + gas turbines</td>
</tr>
<tr>
<td>Italy</td>
<td>Top-down</td>
<td>AC connections from bordering national power system</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>Top-down</td>
<td>AC interconnection from bordering states</td>
<td></td>
</tr>
</tbody>
</table>

The Italian TSO Terna, mainly implements the top-down restoration tests, so far with the support of the neighbouring French TSO RTE and Swiss TSO Swissgrid. Their aim is to re-energize cranking paths to the biggest thermal power stations after a blackout. However, these generators are located in the southern part of the country, far from the interconnected European system, which brings difficulties, mainly in terms of voltage control. In the period between 2012 and 2017, Terna has performed five top-down restoration on-site tests with the assistance from the TSOs in France and Switzerland, as listed in Table 2. Improvements have been made
with the installation of shunt reactors on 380 kV nodes, which allowed longer cranking paths to be energized [12].

Table 2 Top-down restoration tests in Italy [12]

<table>
<thead>
<tr>
<th>Test number #</th>
<th>Year</th>
<th>Cranking path</th>
<th>Cranking path length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2012</td>
<td>France – Valmontone</td>
<td>940</td>
</tr>
<tr>
<td>2</td>
<td>2013</td>
<td>Switzerland – Presenzano</td>
<td>1000</td>
</tr>
<tr>
<td>3</td>
<td>2014</td>
<td>France – Andria</td>
<td>1300</td>
</tr>
<tr>
<td>4</td>
<td>2015</td>
<td>Switzerland – Brindisi</td>
<td>1400</td>
</tr>
<tr>
<td>5</td>
<td>2017</td>
<td>France – Brindisi</td>
<td>1450</td>
</tr>
</tbody>
</table>

During the first test, three hydro power plants near France were synchronized with a total of five switching actions implemented by Terna TSO [12]. However, before the test was implemented on the real EPS, a number of analyses were carried out to examine which are the critical aspects related with the process in order to verify the viability of the procedure. The analyses investigated transient over-voltages and resonance phenomena. From the results conducted, inrush currents and transient over-voltages were observed. In the second top-down restoration test, which was performed in cooperation with Swissgrid TSO, longer cranking path was energized in less time and less switching actions. Again, the cranking path was configured and analysed in advance.

Another example related with EPS restoration in Europe, that uses different approach is implemented by the Irish EirGrid. Their top-down strategy incorporates voltage-source converter HVDC technology provided by the DC link The East West Interconnector (EWIC) connecting Ireland and Great Britain. A black-start test was performed successfully in 2018, nevertheless two key concerns were highlighted. The first is the required short-circuit level of the system in order to change the operation mode from islanded to normal, which could be impossible to achieve during black-start scenario. The second concern is the frequency deviation, which should be smaller when synchronizing the EWIC in comparison to standard deviations allowed for synchronization. On the other hand, bottom-up restoration is provided generally by hydro and gas power stations with black-start capabilities.
The Australian Energy Market Operator (AEMO) uses the hybrid approach for EPS restoration that includes neighbouring interconnections between the states, in addition hydro and gas power plants are used for bottom-up strategy. Their approach in EPS restoration, taking into account their previous experience after the major blackout in 2016, consists of several tasks. In the first step of the restoration, auxiliary power is secured to the larger power plants and the EPS is being prepared to further restoration process. Regularly, in cooperation with the transmission and distribution system operators they review the black-start procedures and on a yearly basis train the operators to reinforce the procedures.

India also implements hybrid strategies in their regular restoration tests. The bottom-up scenarios are implemented on most of the hydro and gas power plants, while top-down approaches are being implemented through interconnections between the states’ TSOs. From their experience, the biggest issues are frequency and voltage control in an islanded operation, operation of protection devices and local controllers [12].

In the Brazilian Interconnected Power System (BIPS), hydro power plants provide main black-start capabilities for the bottom-up approach, whereas the top-down approach uses the interconnections between the independent areas and scenarios involving LCC HVDC. Their aim is to re-energize the 230 kV voltage level in the shortest time possible. In order to prepare for the tests taken on the real EPS, detailed studies are being conducted and the operators are trained for emergency situations as much as possible. Studies include steady-state check of the voltages, thermal limits of lines and generators power output limits. The studies from dynamic point of view focus on transients as a result of switching actions and resonance phenomena. The training exercises using simulators are performed regularly and are perceived as an indispensable tool to ensure adequacy of the processes [12].

2.5. Slovenian power-system restoration plans and experiences

As part of the European interconnected EPS, Slovenia has to prepare plans for EPS restoration as well [2]. This became a subject of special interest in the last few years. For ensuring secure and reliable operation of the EPS, the Slovenian TSO ELES provides several ancillary services, including black-start capabilities. Some of the power plants with black-start capabilities
include: thermal power plant (TPP) Brestanica and hydro power plant (HPP) Fala. The gas
turbines in TPP Brestanica (generating units 1-3 (3x23MW) and generating unit 6 (53MW))
provide black-start capabilities without an external source of power. In case of a major
blackout, the first task should be the re-energization of cranking paths on 110 kV voltage level
to supply auxiliary power to nuclear power plant (NPP) Krško and then, the important loads in
Posavje region. To prove the viability of the scenarios, training exercises are being performed.
Most of the tests were performed only to prove the black-start capability of individual power
plants. Recently, in January 2019, ELES successfully completed a challenging black-start test,
establishing a cranking path to 400 kV voltage level to the substation Maribor with a bottom-
up approach. One of the machines in HPP Fala (25 MW) was operating unloaded, supplying
the 110 kV transmission line Fala-(Karbid)-Pekre Jug, the 110 kV transmission line Maribor –
Pekre I, and one 400/110 kV transformer in the substation Maribor [29]. In the event, the
energization was accomplished by implementing the soft energization method.
Chapter 3

The discussed technical challenges associated with the restoration process should be accurately studied and tested using real-time simulation tool. The most important advantage of the real-time simulation is the fact that it works in continuous real-time, in other words, the simulated EPS behaves in a manner similar as the actual EPS would behave. In this way, real-time simulators enable HIL simulations where the modelled system in the software environment is interfaced with a physical device through the hardware of the simulator, so that its operation is tested before applying them in the actual EPS.

For the simulations performed within this thesis, we used the RTDS simulator at the Faculty of Electrical Engineering, University of Ljubljana. The RTDS performs electromagnetic transient (EMT) simulations to study the dynamics of the modelled system. As mentioned, it is able to capture operations of the network in realistic manner. In continuation, within this chapter, we presented the models of the devices which were used for the EPS models. Furthermore, a brief theoretical introduction in the phenomena related to the components is given, which play an important role in the process of modelling the system.

3.1. Involved device models in network configuration

For the simulation model developed in this work, we used RSCAD software. RSCAD is a graphical user interface designed exclusively for use with the RTDS simulator. The software consists of several modules that allow the user to prepare and run the simulation and to analyse the results. RSCAD/Draft module contains a plane where the user graphically assembles a model using the components available in RSCAD Library. Once the model is completed, it has to be compiled in order to create execution code for the simulator. The interaction between the user and the simulation is via RSCAD/RunTime module. Here, the user controls the simulation through graphical interface containing controls such as buttons, switches, dials or sliders used in the model. For monitoring the operation of the simulation, a number of indicators can be used including meters, plots, lights etc. Each interaction automatically triggers plot updates unless selected otherwise. The acquired results can be saved in different formats or directly
printed from RunTime. Since manipulations with the graphs in RSCAD/RunTime module are often impractical, MATLAB software was used for plotting instead.

Using the generic models of the components from Power System Library in RSCAD, we developed the testing models of the EPS with different electrical network configurations. Additionally, we constructed the control models for the generator, specifically the governor-turbine model and excitation system.

3.1.1. Source model

The equivalent source model, sometimes referred as an ‘infinite power source’, is a simplified representation of a larger part of the EPS. RSCAD contains both one phase and three phase source models. The model, which we used, is designed as a three-phase voltage source behind an impedance. The positive sequence impedance can be chosen as one of the four configurations: R, L, R//L, R- R//L. This component maintains the electrical voltage sine wave’s magnitude, phase and frequency at a given set-point, independently to the changes of conditions in the system to which is connected. In the model, we used R-R//L configuration. Changing the values of the source impedance defines the short-circuit power of the system represented by the source model. The parallel resistance value was typically set to a large value, in that way we basically have a series R-L circuit.

Figure 3.1 Three-phase source model component from RSCAD Library
3.1.2. Transmission line model

In general terms, we use transmission line models which are classified as models with lumped parameters or distributed parameters. Further, the models with lumped parameters can be represented with a series impedance only, π-section model, or T-section model. These models are suitable for short distance transmission lines only. In reality, the electrical parameters are not lumped, they are spatially distributed along the length of the line. If the transmission line is longer, it should be taken into account the fact that the parameters are distributed. The models with distributed parameters are subdivided into constant frequency model and frequency dependent models. The constant frequency model is widely known as Bergeron’s model, based on the travelling wave theory. Usually, we use the terms sending-end and receiving-end of the transmission lines to denote the beginning and the end of the distributed transmission line.

The distributed transmission line travelling wave model is characterized by two values: the surge impedance $Z_0 = \sqrt{\frac{l}{c}}$ and the wave propagation time $v = 1 / \sqrt{l c}$, where $l$ and $c$ are the line inductance and line capacitance per-unit length, respectively. The wave propagation time is practically the speed of light. Therefore, the travelling time between the sending-end and receiving-end of the transmission line with length $d$, is:

$$\tau = \frac{d}{v} = d\sqrt{\frac{l}{c}}$$

(1)

If the transmission line is long, the travelling time will be greater than the solution time-step for the simulation. Generally, with a solution time-step of 50μs, assuming that the wave propagation speed is at speed of light (approximately $v = 3 \cdot 10^8 \text{ m/s}$), transmission line with length over 15 km should be modelled using distributed transmission line model (Bergeron’s model).

Within the RTDS, transmission lines are modelled using distributed parameter models based on travelling wave method. There is a separate RSCAD module available, T-line module, where detailed data for the line is required. If the line’s travel time is shorter than the simulation time-step, the transmission line cannot be modelled as a travelling wave model, therefore it is represented by lumped R-L-C components arranged in π-section model. The π-section model can be used, which is much simpler, requiring basic R-L-C data for the line. Alternatively, the
distributed travelling wave model has an option to force lines shorter than the solution time-step to be considered as π-section models.

![Diagram of π-section model and Travelling wave model]

**Figure 3.2 Transmission line models from RSCAD Library**

3.1.2.1. Travelling waves along the distributed transmission line model with open receiving-end

In this subsection it is reasonable to give a brief theoretical introduction in the travelling wave’s phenomenon in transmission lines. In a transmission line, the voltage is launched in form of electromagnetic travelling wave along the line, spreading with finite velocity, determined previously by equation. Further, we assume that the transmission line has an open receiving-end, or in other words it is connected to an infinite impedance. Thus, as a result of a switching event or, when an atmospheric discharge occurs, a transient phenomenon occurs in the first milliseconds after the event, illustrated in Figure 3.3. At the open end of the transmission line a reflected wave \( U_2 \) is formed travelling in the backward direction. This wave is superimposed to the original one \( U_1 \), therefore the transient voltage wave \( U_3 \) has two components, one travelling in forward direction (original) and the other in the opposite direction (reflected). For an open-end transmission line the reflection coefficient \( a \) is unity [4]. Therefore, the reflected voltage wave has the same sign as the original wave \( U_2=aU_1=U_1 \), which means that the transient voltage wave at the receiving end of the line is a double value of the original voltage wave \( U_3=2U_1 \).
3.1.2.2. Ferranti effect

Another effect related to the transmission lines, which is not a dynamic phenomenon, but it should be also taken into account, is the so-called Ferranti effect. The Ferranti effect refers to the rise in voltage along a transmission line with open receiving-end. This effect is more pronounced in longer transmission lines. In this case, when the transmission line is unloaded, the voltage at the receiving-end $U_R$ will always be higher than the voltage at the sending-end $U_S$ according to:

$$U_R = \frac{U_S}{\cos(\beta \cdot d)} \quad (2)$$

where $d$ is the line’s length and $\beta$ is a factor dependent of line’s parameters ($\beta \approx \sqrt{x \cdot b}$).
3.1.3. Transformer model

RSCAD Library contains different types of power transformer models including two and three winding transformer models, both current and voltage measurement transformers, as well as autotransformer models. The models enable consideration of hysteresis and saturation. Including saturation allows specifying data for defining magnetizing characteristic of the ferromagnetic iron core. The model enables dynamic adjustment of the residual flux allowing the user to specify the initial value of the residual flux in the individual phases.

![Transformer model from RSCAD Library](https://example.com/transformer_model)

In the model we used a three-phase, two-winding, non-linear transformer. Standard transformer data is required for the model: transformer rating, base frequency, winding connections, primary and secondary rated voltage, leakage inductance and losses.

3.1.3.1. Basic concept of transformer’s inrush dynamic phenomena

Switching a transformer on AC voltage causes a well-known inrush transient phenomenon, which is more unfavourable in case when the transformer is not loaded. Due to the non-linear magnetic characteristic of the transformer’s ferromagnetic core, switching the transformer on, might drive the core into saturation. Figure 3.5 illustrates the non-linear relation between the flux and the magnetization current, or more commonly known as B-H magnetizing characteristic curve. Namely, the magnetization of the core exhibits a hysteresis characteristic,
as illustrated in Figure 3.5, retracing different paths under different voltages applied. Increasing the applied voltage will demand more and more flux, since the flux is proportional to the integral of the applied voltage. This leads the core in saturation region, where a slight increase in the flux results with large increase in the current, known as inrush current.

In steady-state operation, the relation between the voltage, flux, hysteresis loop and magnetization current is given in Figure 3.6. The operating peak flux is located near the knee of the hysteresis loop. The magnetizing current in normal operating conditions has magnitudes between 0.5% and 2% of the rated current [21]. Figure 3.6 presents the qualitative representation between the voltage, flux and current when a transformer is switched on. Assuming that the energization happens in the moment when the voltage passes through positive zero-crossing, the flux will increase to a double value of the maximum flux ($\Phi_m$). Such an increase in the flux, demands an excessive increase in the magnetizing current, leading the transformer into saturation.

Figure 3.5 Non-linear magnetization characteristic curve of a transformer [21]
Additionally, we assume that the transformer was previously operating normally and then it was de-energized. When the transformer is switched-off some flux following the hysteresis loop may remain in the core, known as residual flux ($\Phi_r$). This flux acts as an offset that may get the transformer into deeper saturation during its subsequent energization. In such case, the flux can reach up to a value of $2\Phi_m + \Phi_r$, resulting in even larger inrush current.
The severity of the transient phenomena due to energization of non-loaded transformer depends on the moment of switching and the level of residual flux in the core. The residual flux has a stochastic character and cannot be predicted. However, it is likely that the transformer will have a certain level of residual flux, in view of the fact that the operating peak flux before the transformer was switched off, is located near the knee of the magnetic curve. Additionally, taking into account the instance of switching, i.e. the value of the voltage at the moment of switching, there are several possible cases that can happen upon. The worst condition is assuming a high degree of residual flux in the core and switching at instance when the voltage is in positive zero crossing, invoking the highest DC component of the flux \[\Phi_r\]. Thus, the phenomenon is more complex if the level of saturation of the transformer’s magnetic circuit is higher. Typical values of the residual flux according to literature [4] and [21] are 20\% to 70\% of the rated flux. Since the level of saturation is unknown beforehand, the applied residual flux in the model is assumed to be at default value of 60\% within RSCAD [23]. The control logic of closing the circuit breakers for energizing the transformers is modelled to demonstrate the worst condition of switching. With a switch-control command the user closes or opens the circuit breakers. The circuit breaker closes when the voltage signal has passed through zero, which is ensured by the zero-crossing detector. The point on wave energization defines the
angle when the circuit breaker is closed and is controlled by the user in the RunTime using slider. Each circuit breaker is controlled by a specific control signal name.

3.1.4. Synchronous machine model and controls

The synchronous machine model is a three-phase machine which is specified to work as a generator, converting the mechanical power of the prime mover to an electrical power. Inputs and outputs for the machine voltage controller are provided via the signals $E_f$ (field voltage), $I_f$ (excitation current), $V_{mpu}$ (voltage at the machine terminals). Per-unit torque produced by the turbine governor is interfaced to the machine via the $T_m$ signal, whereas the generator’s speed is available as an output signal $W$ of the generator. Required parameters for the synchronous are base frequency, rated power (in MVA), rated RMS line-to-line voltage, electrical data (stator leakage reactance, stator resistance, d-axis and q axis reactances, d-axis and q-axis sub-transient and transient time constants) and mechanical data (inertia constant, mechanical damping). The model configuration allows the user to choose whether the generator initial speed at first time step is zero, or rated. A lock/free switch is used for a proper initialization during simulation start-up. Table 3 gives the parameters for the SG unit used in the test model.

![Figure 3.8 Synchronous machine model from RSCAD Library](image-url)
Table 3 Parameters for SG unit

<table>
<thead>
<tr>
<th>SG</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_n$ [MVA]</td>
<td>32</td>
</tr>
<tr>
<td>$P_n$ [MW]</td>
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</tr>
<tr>
<td>$U_n$ [kV]</td>
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<tr>
<td>$f$ [Hz]</td>
<td>50</td>
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<tr>
<td>$T_a$ [s]</td>
<td>13.38</td>
</tr>
<tr>
<td>$R_a$ [p.u]</td>
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</tr>
<tr>
<td>$X_{ss}$ [p.u]</td>
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</tr>
<tr>
<td>$T_d''$ [s]</td>
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<tr>
<td>$X_d''$ [p.u]</td>
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</tr>
<tr>
<td>$T_d'$ [s]</td>
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</tr>
<tr>
<td>$X_d'$ [p.u]</td>
<td>0.182</td>
</tr>
<tr>
<td>$X_d$ [p.u]</td>
<td>2.22</td>
</tr>
<tr>
<td>$T_d''$ [s]</td>
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</tr>
<tr>
<td>$X_d''$ [p.u]</td>
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</tr>
<tr>
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</tr>
<tr>
<td>$X_d'$ [p.u]</td>
<td>0.25</td>
</tr>
<tr>
<td>$X_d$ [p.u]</td>
<td>2.00</td>
</tr>
</tbody>
</table>

3.1.4.1. Governing system

The prime movers convert the energy of the fuel into mechanical energy that drives the shaft of the synchronous generator. The governing system is responsible of controlling the prime mover in that way maintaining the frequency and the power output. The frequency control, hence the speed control of the generator, is done by a speed governor, whose task is to detect the change in speed, or frequency, and adjust the turbine valve, in that way changing the mechanical torque, resulting in correction of the speed. There are mainly two types of speed control: isochronous and speed-droop. The governor is said to be *isochronous* if the speed control function maintains constant speed regardless of the load, i.e. it always returns the speed (frequency) to the reference value. The *speed-droop* type of control has a linear relation between speed (frequency) and power output. The characteristic of frequency vs. output power (see Figure 3.9) defines the decrease by fixed percentage of frequency when the generator’s power output goes from no load to full load condition. Thus, an isochronous mode of operation contributes with a zero value of droop, while in droop mode the slope of the characteristic is defined by a fixed value, usually marked with $R$ (droop).
In a black-start scenario with bottom-up approach, the operation of the governors has an important role for maintaining stable frequency. According to the literature, it is desirable, particularly in isolated systems, to have one governor in isochronous mode that will hold the frequency nearly constant. For the purpose of investigating the operation of both types of the speed governors, we constructed custom model of the governor using the control function.
blocks available in RSCAD Library. In [5] and [6], detailed mathematical models for the prime
movers and speed governing systems are provided. However, we did not consider the described
complexity of the model in this thesis, because the objective was not a detailed design of the
control system of an actual model. We used appropriately simplified models, which are
sufficient for the accuracy of the basic operation of the model, based on the examples in [5]
and [6]. The governing system model illustrated in Figure 3.11 was designed. The speed
controller is provided with proportional-integral (PI) action. The parameters of the proportional
gain $K_p$ and integral gain $K_i$ can be obtained by adjusting the associated slider controls in
RunTime interface. In the model, the derivative portion of a PID controller was not
implemented. The droop factor $R$ is defined by Equation (3), which gives the relationship
between the load change and the speed change of the generator as it was previously illustrated
in Figure 3.9. The governor model allows both isochronous and speed droop governing mode.
For a speed droop governing mode it was initially set to a typical value of 5%. When operated
in isochronous mode, $R$ was set to a value of 0.01% because value of zero is constrained by the
software.

$$R = \frac{\text{No load speed} - \text{Full load speed}}{\text{No load speed}}$$  \hspace{1cm} (3)

![Figure 3.11 Simplified block-scheme of a governor-turbine model](image)

The actuator is represented by a first order transfer function (parameters $G_1$ and $T_1$), whereas a
compensation component (parameters $G_2$, $T_3$, $T_4$) was used, in order to represent a time delay
in additional components until the torque adjusts. The input signals for the speed governor are
the reference speed in per-unit and the actual speed of the generator converted in per-unit as
well. The reference speed can be set by adjusting a speed reference slider, or following a ramp increase.

### 3.1.4.2. Excitation system

The other key control system of the generator is the exciter, which provides direct current (DC) to the field winding of the synchronous generator. The purpose of the excitation system is to maintain the terminal voltage of the generator at a specific value. As well as the governor model, we designed an excitation model using general control functions blocks. The model that we designed is a simplified model of the IEEE Type 1 excitation system [31] that neglects the saturation effects. *Figure 3.12* shows the block diagram of the model, including amplifier and exciter represented by first-order functions.

![Figure 3.12 Simplified block-scheme of an excitation system](image)

### 3.1.5. Load model

The model, which we used to represent the loads is a dynamic load component available in RSCAD Library. This component can represent different types of load in the EPS. Typically, it adjusts the active and reactive power to a percentage of the power set points. Otherwise, if the model is set as constant impedance, it implies that is no longer a dynamic load. In the configuration menu, the user can choose how to control the power. One way is to vary the power through external control inputs. For the test system configurations, we modelled the load with constant impedance as a parallel R-L circuit. Because of time constraint reasons, we did
not consider a detailed modelling of the load. The active and reactive power of the load can be set and changed once the simulation is running, via external controls, in particular using slider controls.

![Dynamic Load Model](image)

Figure 3.13 Dynamic load model from RSCAD Library

3.1.6. Other components

Circuit breakers are added to allow components to be connected in the EPS model. The opening and closing of the breakers is controlled by an external control signal, specific for each circuit breaker. When the circuit breaker is closed it is represented by a resistance, which is set through the configuration menu of the component. The value of the resistance is set as small as necessary so that it is negligible in comparison with the rest of the elements. In the model, we assumed a default value of 0.01 ohms for all the cases.

We incorporated a variety of other components in the model, such as different types of meters, logic controls, switches, push buttons, synch-check relay, timers, math functions etc.
Chapter 4

4.1. Simulation of top-down approach

This section focuses on the top-down approach for power-system re-energization after a blackout. We analysed a simple EPS model by means of simulations in order to identify possible problems when applying this strategy. It should be noted that the EPS considered here is simply an example to illustrate the concept and the phenomena to be expected. The actual behaviour varies from system to system and the existing conditions at the moment of energization. The studied EPS model illustrated on Figure 4.1 consists of an equivalent source model representing the neighbouring transmission system in normal operating conditions, whereas the transmission line and the power transformer are part of the area in blackout that should be re-energized. In the simulations conducted, we did not consider surge arresters. Top-down approach re-energizes the collapsed part of the EPS from higher voltage level in this case 400 kV. Therefore, at the starting point of the restoration process, the transmission line and the transformer were not loaded, since loads are spread on lower voltage levels.

![Figure 4.1 EPS model configuration for top-down re-energization](image)

We performed several simulations, which provide insight into the dynamic phenomena at the moment of switching the circuit breakers. In first place, we started the simulation with normal operating conditions when the transmission line and the transformer were connected to a stable operating EPS. Then we disconnected the transformer and the transmission line, in that way representing the outage of the elements due to some contingency. Disconnecting the
transformer, according to the control logic of the circuit breaker, left residual flux in the core of the transformer. Subsequently we energized the transmission line and the transformer using the external secure EPS, by closing the circuit breakers CB1 and CB2.

4.1.1. Energization of unloaded transmission line

First, we energized the transmission line by closing the circuit breaker CB1. Specifically, the length of the line was set to be 50 km and the source had short-circuit power 50 GVA. *Figure 4.2* shows the typical switching surge effect. The switching surge contains high frequency components that decay quickly. In this example we can notice that the duration of the switching surges is not much more than one frequency cycle, after which are followed by a normal steady-state voltage. As shown on *Figure 4.2*, the switching surge has the highest peak at the open receiving-end of the line, where the effect of the reflecting travelling wave is pronounced.

![Graph showing monitored voltage after the energization of the transmission line](image)

*Figure 4.2 Monitored voltage after the energization of the transmission line*
We performed another set of simulations changing the length of the transmission line. In this example we observed the Ferranti effect. Figure 4.3 shows line-to-line RMS values of the voltages at the beginning and at the end of the transmission line for several different lengths of the line. With the 50 km transmission line used here, the Ferranti effect is very small, practically not evident. However, when the length is increased to 300 km, we can clearly observe the Ferranti rise of the line-voltage for approximately 8%. Therefore, when energizing long transmission lines, shunt reactors should be used in order to limit the effect.

![Figure 4.3 Ferranti effect](image)

4.1.2. Energization of the unloaded transformer

In this section, we focus on the analysis of temporary over-voltages as a result of transformer’s energization. Several parameters including the source impedance, system capacitances, load levels and circuit breaker closing times, have an impact on transient over-voltages ([14], [15]). We investigated the impact of the source impedance and the length of the transmission line on transient over-voltages. Initially, we considered 50 km length of the line and a transformer with rating 300 MVA for the part of the system that should be re-energized. The external secure network from the neighbouring EPS is presented by an equivalent source. In the first example
we considered a strong external grid, in other words, we set the impedance of the source to low values, specifying short-circuit power of approximately 50 GVA.

The transmission line is already energized when we switch CB2 energizing the transformer. As expected, the inrush phenomena appears as the transformer is driven into saturation. In Figure 4.4 we see the typical inrush current \( i_m \) waveform and the corresponding harmonic content as well. As we can see in Figure 4.4, the inrush current is rich in harmonics, especially in even harmonics. The second order harmonic component is dominant. Typically, the harmonics’ magnitudes decay over time. However, we can notice that for example the 4th order harmonic component does not have the highest magnitude at the very first instance when the phenomenon occurs, but it is increased after several milliseconds.

Figure 4.4 Inrush current and its harmonic content

Figure 4.5 shows the primary side voltage of the transformer after the energization, where some transient voltage peaks can be observed. Since we considered that the external EPS is strong, the over-voltages are not a concern in this case.
For the next case, we increased the values of the system impedance, which complies with lower short-circuit power, approximately 10 GVA. The results presented in Figure 4.6 show that the energization of the transformer provokes higher transient over-voltages in comparison with the previous case. Namely, the increase of the source impedance complies with lower resonant frequencies. The inrush current, as we showed previously is rich in low-order harmonics. Hence, the harmonic components of the inrush current and the inductances and capacitance in the system interact, causing higher transient over-voltages.
Another scenario that we considered is the energization of the transformer together with the transmission line, therefore CB2 was closed and then we closed CB1, simultaneously energizing the transmission line and the transformer. The external grid had 10 GVA short-circuit power, the transmission line was 50 km long and the same transformer was used as previously.

In Figure 4.7 we observe that severer switching resonant over-voltages occur in case when the transmission line and the transformer are energized simultaneously.
To summarize, one weak spot of the top-down restoration approach is the energization of unloaded transmission lines and transformers in the initial step of the process. The conditions are unfavourable when the transmission line and the transformer are not loaded, which results in higher amplitudes of the switching transient. In view of this fact, the first transmission paths energized preceding the load, should not be long, in order to avoid higher capacitances and inductances. In addition, it is reliant of the neighbour’s EPS ability to supply power. In short words, if the neighbouring EPS is strong, the re-energization procedure should not be a concern. However, depending on the prevalence of the blackout, the neighbouring system’s may also be affected, therefore the short-circuit power may vary. Moreover, in case of a wide-spread blackout, the help of the neighbouring EPS may not be available. In that case, another restoration approach is implemented, which is described in the following section.

4.2. Simulation of bottom-up approach

In continuation, we study the bottom-up approach for EPS re-energization. The bottom-up method involves formation of electrical islands from black-start generating units in the control area, which are eventually synchronized. In Chapter 2, different aspects of the process were introduced. From the point of dynamic analysis, it is important to demonstrate the system’s behaviour when applying different switching actions. Therefore, we simulated both switching options, namely the sequential closing method and the soft energization method.
4.2.1. Scenario 1 – Sequential closing of the circuit breakers

In the first scenario, we considered sequential closing of circuit breakers. In this case, the SG was initially running at rated speed and its terminal voltage at nominal value, at no load condition. Then, we closed the circuit breakers in succession, energizing the grid elements one by one. The dynamic model of a typical black-start scenario comprises a synchronous generation unit with black-start capability, power transformer units and transmission lines. Specifically in the model we included synchronous generator with rating 32 MVA, step-up transformer with rating 28 MVA and a power transformer with rating 300 MVA. Figure 4.8 presents single-line scheme of the developed testing EPS model.

![Figure 4.8 Single-line scheme of EPS model for bottom-up energization scenario](image)

After the model was built, including the RunTime interface, we performed real-time simulations to validate the black-start process in terms of dynamic behaviour. We assumed different initial conditions in this scenario, regarding to the transformer energization at no-load condition. Namely, this refers to the moment of switching and the residual flux in the transformer’s core. The severity of the transient phenomena due to energization of non-loaded transformer depends on the time of switching and amount of residual flux in the core. Regarding to the switching instance, i.e. the value of the voltage at the moment of switching, there are several possible cases that can happen upon.

Similarly, like in 4.1, we started the simulation with all the elements energized and the circuit breakers closed. Then, by opening the circuit breakers, we de-energized the system, leaving a residual flux in both of the transformers, namely 60% of their rated flux, which corresponds with the results shown on Figure 4.9 and Figure 4.10. We should stress that identical time axis
labels do not denote that the switching actions were performed simultaneously. Instead, the labels should be referred to as being relative to the beginning of individual process/action.

Figure 4.9 Residual flux in transformer TR2 after initial de-energization

Figure 4.10 Residual flux in transformer TR1 after initial de-energization

From analysing the diagrams in *Figure 4.10* it can be seen that the maximum value of the residual flux is in phase A and phase C of opposite polarity. The residual flux in phase B is practically zero. We assumed simultaneous switching of all three phases, when the voltage in
one of them is at zero value. The transformer can be switched on when any of the phases is at zero voltage, while the other two phases and are at 86.6% of the maximum voltage, one is positive and the other is negative. For the worst-case scenario we supposed phase A is at zero value of the voltage, since the residual flux in phase A has a maximum value. By switching the first circuit-breaker CB1, we energized the step-up transformer TR1 that is accompanied by a well-known dynamic phenomenon, being magnetizing current with high magnitude, referred as inrush current due to magnetization of transformer’s core. In Figure 4.11 we can notice that the currents in different phases have different magnitudes depending on the amplitude of the corresponding flux, shown in Figure 4.12. Due to the highest value of the residual flux before switching, consequently the inrush current has the highest amplitude in phase A. We can clearly see that the magnetizing current has non-sinusoidal shape, i.e. is asymmetrical. The phenomenon lasts for a short period of time and the inrush current eventually decays to normal levels. By observing Figure 4.13 it can be noticed that switching the step-up transformer caused rapid voltage dip at the generator’s terminals. Noticeably, the asymmetrical magnetizing current causes asymmetrical voltage dip as seen from the voltage waveform in Figure 4.13B). We can observe in Figure 4.13A) that each phase has a different magnitude of the voltage dip accordingly to the level of saturation. Here, we have to mention that for the 1-phase RMS measurements we used a meter which has a different refresh-rate and it is not able to detect the changes according to the simulation time-step. In Figure 4.14 we can observe the rotor angle oscillation due to transformer’s energization. In regards to the transient over-voltages, the energization of the step-up transformer was not a concern.
Figure 4.11 Magnetization current of TR1 after its energization

Figure 4.12 Flux in TR1 after its energization
4.2.1.1. Impact of the residual flux on the inrush current magnitude

In the previous case we assumed switching the transformer on, when there is a significant level of residual flux in phase A. In order to present the impact of the level of residual flux on inrush current by comparing the results for current in phase A, in the next simulation we assumed no residual flux in the core. Figure 4.15 illustrates the inrush current in phase A. We can see that
the peak value of the inrush current reduced to about 60% in comparison with the results obtained earlier.

Figure 4.15 Effect of the residual flux on the amplitude of inrush current

In the next step of the restoration process, we energized the transmission line. Figure 4.16 shows the monitored voltage on the secondary and primary winding of the transformer TR1 when we performed this action. The switching action caused resonant over-voltages, with a maximum magnitude of 1.8 p.u., as seen on Figure 4.16A).
After that, we energized the second transformer TR2 in the main substation, which is the crucial steps in the process, since the power rate of the transformer (300 MVA) is large in comparison with the capacity of the local generator (32 MVA). The system has low inertia since there is only one generator operating. The SG in this case is characterized by a short-circuit ratio (SCR) which is quite low, specifically 0.45. Therefore, it was expected that the SG will have difficulties to maintain the voltage when major voltage change occurs. Switching on the transformer TR2 in the most unfavourable instance, i.e. at switching angle 0 degrees, invoked large inrush current which we can observe in Figure 4.17. In another scenario, we chose different switching angle, namely 45 degrees. For this example the inrush current is shown in Figure 4.18 where we can observe that its amplitude is reduced in comparison with the previous case. In Figure 4.19 we can see weakly damped temporary over-voltages at the 110 kV voltage level, caused by the energization of TR2. Basically, this is associated with parallel ferroresonance phenomenon, created by the inductances and capacitances in the system interacting with the inrush current. In case when the resonant frequencies are near the
frequencies of the harmonics contained in the inrush current, the result is higher voltage at the transformer’s terminals. It is likely that such a phenomenon is present in a black-start scenario, because the system is not (or lightly) loaded.

Figure 4.17 Inrush current in TR2 as a result of energization in the worst-case switching condition

Figure 4.18 Inrush current in TR2 as a result of energization (45 degrees switching angle)
Another phenomenon that we observed in this case is associated with the behaviour of the transformer already operating, as a consequence of another transformer being energized. In the present case, we energized the second transformer TR2 while the first transformer TR1 was already in operation. As a result, this caused a much more complex phenomenon than the already known inrush phenomenon, the so-called series sympathetic inrush phenomenon. To understand the phenomenon better, a brief qualitative explanation of the basic characteristics of sympathetic inrush is needed. During inrush phenomenon, at the moment of energization, flux linkages of the transformers contain AC and DC components. The DC component decays exponentially over time, as the inrush phenomenon vanishes. The DC components of the flux linkages of both transformers are determined by an exponential components, however not the same, therefore both of them have different decay times. An important thing to note is that the DC components have opposite sign. For a deeper understanding, the derivations of the equations and the physical background can be found in [17]. Namely, when TR2 is switched on, the inrush phenomenon appears, therefore a DC component is present. At that instance, TR1 is not yet affected by the inrush phenomenon and it is still operating in the linear part of the magnetization characteristic (see Figure 3.5), hence its DC component is zero. Over one period of the voltage, the DC components are shifted along the magnetization curve each moment in an opposite polarity saturation region. The inrush current of TR1 is then gradually increased. The interaction between the two transformers at the 110 kV voltage level is shown in Figure 4.20 and Figure 4.21, for the different energization conditions considered. We can observe that the currents are not simultaneous, but 180° apart. Another thing to see, is that the inrush current of the transformer that was already in operation has lower amplitudes. Figure 4.19 Over-voltages after energizing TR2
4.22 illustrates the magnetization characteristics of TR1 and TR2, where again, the opposite polarity saturation is evident.

Figure 4.20 Sympathetic inrush phenomenon between TR1 and TR2 normed at 110 kV (worst-case scenario)

Figure 4.21 Sympathetic inrush phenomenon between TR1 and TR2 normed at 110 kV
After the initial event of sympathetic interaction, both DC components of the flux linkages start to decay towards zero. As a result of the opposite polarity, the decay is slower. This is the reason why this inrush phenomenon lasts longer compared to the energization of a single transformer. The sympathetic interaction can lead to incorrect operation of the differential and overcurrent protection of the already connected transformers in the system [9].

Next, we were interested in investigating the impact of the switching instance on the sympathetic inrush phenomenon. Specifically, we analysed the amplitudes of the currents focusing on the effect of the switching angles considered. The results obtained from the simulations are presented in Figure 4.23. We observe that shifting from zero degrees to 90 degrees, decreases the intensity of the interaction.

The phenomenon of sympathetic interaction between transformers is considered to be more evident in ‘weak’ systems, in this respect under no load or lightly loaded conditions [18]. In some literature review, this phenomenon is named as recovery-inrush, or, pseudo-inrush phenomenon ([18], [19]). In fact, such a phenomenon is apparent during recovery of the voltage after a voltage dip occurs.
As stated earlier, applying this method for energization can lead to undesirable effects such as triggering of protection devices. The presence of the residual magnetism increases the effect even more.

Up to this point, we can conclude that the classical method based on sequential switching of the transmission lines and transformers leads to over-voltages, oscillations and large inrush currents, which may cause electrical stresses on the power equipment, especially during a black-start operation due to a low generation capacity. In order to avoid these undesirable effects, an alternative re-energization approach was implemented. Therefore, the following section analyses this method for bottom-up re-energization, namely the soft energization method.

4.2.2. Soft energization method

For this scenario, we implemented the soft energization method, to illustrate the alternative method for re-energization of the system. As we described in Chapter 2, according to this principle, all involved components (synchronous generator, transformers and transmission lines) are firstly connected to each other, non-energized. Without voltage excitation, we run-
up the generator and afterwards, we gradually increased the terminal voltage. We used the same system configuration and components for the testing model as in the previous scenario. This case was designed in a way of running the generator up either automatically, or manually using the governor and exciter controls incorporated in the user interface. Detailed instructions for the user interface are given in Chapter 5. In continuation, the results are presented when implementing both manual and automatic mode.

4.2.2.1. Manual start-up of the generator

In the first step of the process we started-up the generator to run from a standby condition to rated speed without excitation. At the beginning of the simulation all controls were set to zero values and “Manual” control mode was activated. Once the simulation was running, we increased the reference speed in 10% step-wise changes. Figure 4.24 shows the increase in the generator’s angular speed $w$, as a result of the adjustment of reference angular speed $w_{ref}$ from zero value to 0.1 p.u. By performing this action, the frequency increased to 5 Hz. Subsequently, with few more interactions, we established the rated frequency of 50 Hz, as seen in Figure 4.25.

![Figure 4.24 Step-response of angular speed due to a 10% increase of reference speed](image-url)
The next step was to increase the voltage, for which the same principle was applied. We adjusted the reference voltage $V_{ref}$ in that way increasing the excitation current, which resulted in voltage increase at the generator’s terminals. In Figure 4.26 we can see the terminal voltage increase when we adjusted the reference $V_{ref}$ from zero to 0.1 p.u. In the same way, we continued the excitation process, gradually adjusting the reference with a step of 0.1 p.u. Figure 4.27 shows the establishment of the rated voltage at SG terminals in the final increase of the reference from 0.9 p.u. to 1 p.u.
4.2.2.2. **Automatic start-up of the generator**

Another option in the model enables automatic start-up of the unit, which is presented in continuation. Specifically, for this case we set the frequency to be increased 1 Hz/s, following a ramp increase of the reference speed as shown in Figure 4.28. By the time of frequency increase, the voltage reference was kept on zero value. When the frequency was at nominal value, we set the increase of the terminal voltage in a similar way, by specifying a time range in which the voltage should increase from zero to nominal value. Figure 4.29 below presents the monitored voltage on the buses for each voltage level — the voltage increased in few seconds.

![Graph](image-url)
We can see that there are no transient over-voltages, when applying soft energization method. By implementing the soft energization method we have a full control over the excitation process. However, in case when the residual flux was considered, as expected, results (see Figure 4.30 ) showed that building up of the flux starts with the offset due to the residual magnetism. When residual flux was not taken into account, the results shown on Figure 4.31 confirm the advantage of applying this method of re-energization. Dynamic transients such as inrush phenomena are avoided.
**Figure 4.30** Flux and magnetizing currents during soft energization (residual flux is considered)

**Figure 4.31** Flux and magnetizing current during soft energization (no residual flux)

The assessed simulation results showed that it is possible to establish voltage on the 400 kV transmission network with smaller machines, without any problems with the connection of larger transformers. However, it should be noted, that the protective relays of the involved EPS elements must be set in such a way that they do not prevent operation in conditions at reduced voltages.
Chapter 5

5.1. Synchronization process

The next step in the re-energization of the system involves synchronization between the re-energized areas or islands. Namely, to re-establish the integrity of the system, the energized paths must be synchronized. Integrating separate parts of the system increases system inertia and the stability of the system, achieving better redundancy. This is an important step in the process of restoring the system after blackout since it increases the capability of the area to pick up larger loads, consequently increasing the stable operation of the system. Aside from the benefits, the synchronization of the re-energized islands brings challenges in maintaining stable frequency and voltage, due to the lack of a bulk system. Therefore, it is necessary to analyse the parallel operation of two generators in islanded operation.

The synchronization should not be underestimated because, if it is not done correctly, especially in the case of restoration process, it can cause severe damage to the equipment or possible shutdown of one or both areas. ENTSO-E likewise NERC, emphasise the importance of evaluating of the capability of the areas to be joined, in terms of frequency and voltage maintenance, as well as to share the control in enlarged system ([1],[27]).

Considering this, for the next step of the model development, we included a synchronization procedure. This way, we examined the model in terms of the response of the generators’ controls prior and after the synchronization, which is crucial for a successful re-energization of the system. We implemented the pre-assembled model of a synch-check relay, which ensures successful synchronization between two systems once the conditions for synchronization are met. It determines the difference in the synchronizing variables from the voltage waveforms inputs. We considered the tolerance range for the voltage and frequency deviations to be the default values from the synch check relay. The allowable frequency difference was set to 0.1 Hz, while the permitted voltage difference was 5%. The phase angle difference should be as close to zero degrees as possible before closing the breaker. In this case, we set the synchronization check relay to allow synchronization if the voltage angle difference is less than 10 degrees. In addition, we also added a synchronizer designed in the RunTime module that
monitors the synchronizing variables, includes voltmeters and frequency meters for simultaneous comparison and provides vector display representation of the voltages, as illustrated later in Figure 5.6, Figure 5.7 and Figure 5.8. One of the voltage vectors is set as a reference at zero degrees. If there is a frequency mismatch between the systems, the other vector rotates proportionally to the frequency difference. When the frequencies are the same, the voltage vectors are stationary indicating the phase angle difference.

Before the synchronizer was applied to the black-start scenario models, we carried out test simulations such as synchronization of a generator to an infinite source bus, to see if there are any evident problems. No such problems were encountered during these preliminary tests.

5.2. Parallel operation of two synchronous generators

In continuation, this section evaluates the parallel operation of two synchronous generators on a common bus. For this purpose, first we designed a simple model, comprised of two synchronous generators with step-up transformers, sharing a load on a common bus. The generators were equipped with governors and exciters. Initially, both machines had identical data set and controls. With the help of the input controls of the AVR models and the speed governors in both machines, the voltage and the frequency can be adjusted to match values for both generators. After start-up of both machines at no load condition, their frequencies had equal values and the terminal voltage values match too. The phase angle difference was brought to a desired value by adjusting the torque in one of the machines and then, the synchronous generators were synchronized.

![Figure 5.1 Two-generators sharing a load on a common bus](image)
5.2.1. Operation mode of governors

Once we had the generators synchronized, it was important to keep the frequency stable. Due to the lack of bulk system, the governor’s operation mode plays important role for the stability of the system. Previously, Chapter 3 familiarized us with the different operation modes of the governors. In this section, we examined the operation modes through simulation results.

5.2.2. Speed-droop control

In the first case, the generators with identical data set were equipped with governors operating with speed-droop characteristic. Specifically, both had the same droop R=0.05 (5%). Furthermore, the generators were loaded with 1 MW each, operating at a common frequency of 49.9 Hz accordingly to the speed droop control. When increasing the load for 3 MW, the power output of each generator was increased for 1.5 MW, as presented in Figure 5.2A specifically for Machine 1. The machines share the total 5 MW load, each having a power output of 2.5 MW. Naturally, two generating units operating in droop control share load at the point of intersect of their characteristics, in this case 49.7 Hz. To bring back the frequency at rated value, we adjusted the load reference through the load reference slider. In this way, each new value of the load reference moves the P-f characteristic upwards or downwards, adjusting the operation set-point of the SG. However, the slope of the characteristic remains the same and is defined by the droop value. First, we adjusted the load reference for Machine 1 and subsequently the load reference for Machine 2. Adjusting the load references to 0.1 p.u. for both generators, brought the frequency to 50 Hz as seen Figure 5.3. This case verified the operation of the governors in speed-droop control. Additionally, we carried out another set of simulations, implementing different droop values and the results were confirmed again – each machine had a power output according to the droop characteristic.
Figure 5.2 Power output of Machine 1 and frequency at the common bus after increasing the load

Figure 5.3 Frequency at the common bus as a result of load control implementation
5.2.3. Isochronous and speed droop control

Regarding the isolated operation of generators, it is proposed that one generator should be responsible to hold constant or flat frequency regardless of the load, i.e. operating in isochronous mode. Isochronous governors can be used on stand-alone generators but not for interconnected generators, both in isochronous operation. First, we should note that two (or more) generators cannot work both (all) with isochronous control. As soon as there is a change in load, frequency swings occur back and forth around an equilibrium point. The reason behind this is that governors generally interact with each other, which might cause unwanted undamped oscillations or the opposite control actions. What happens is that both machines will sense the change in speed and at the same time will be trying to fix it. That is their natural behaviour; they are not disposed to sharing load. Each governor wants to control the frequency and each one responds on the change of speed. One is accumulating the error trying to speed up the system, whereas the other is trying to slow it down.

For the next case, we set Machine 1 to operate in isochronous mode and Machine 2 to operate in droop mode. Without a load control enabled by the load reference adjustment slider of Machine 2, which is operating in droop mode, any change in the load resulted in change of the power output of Machine 1 operating in isochronous mode. Namely, in case when we added a 5 MW load, Machine 1 carried out the total load, in order to maintain the system frequency, while Machine 2 was not loaded. Next, in order to increase the power output of Machine 2, we enabled its load control, i.e. we adjusted the load reference for Machine 2. The latter change resulted in increase of the power output of Machine 2, accordingly to the adjustment of the load control, in this case specifically to 2.5 MW. In the same time the output of Machine 1 operating in isochronous mode adapted to the changes, reducing its power output for 2.5 MW. Therefore, in case when there is one machine operating in isochronous mode, a load control is needed for the machines operating in droop mode, otherwise the isochronous machine will attempt to carry up the total load, until the load does not exceed the maximum power output of the machine.

5.2.4. Unstable operation of governors

The following example presents unstable operation of the frequency control system. For this case, we did not use identical data for both of the governors. We changed the time constants of the controllers and the gain constants were not adjusted properly. In case when the proportional
gain of the governor for SG2 was increased to higher value, the response of the system became faster, but caused oscillations of the frequency that become larger, consequently the frequency became unstable. The results from this test are presented in Figure 5.4. In this case the governors operate against each other, resulting in unstable frequency.

![Figure 5.4 Unstable operation of the governors](image)

This example emphasizes the importance of investigating the operation of governors when synchronized together. Especially, it is important in case when the governors are not from a same manufacturer and do not have same operating characteristics and parameters.

5.3. EPS model for black-start scenario

After the development of the test models and testing different approaches regarding to the EPS restoration process, we developed an EPS model for black-start scenario (Figure 5.5), implementing the bottom-up approach restoration. The model includes two separate cranking paths used for restoration of the EPS. In this case, the machines had different data sets, given in Table 4.
Table 4 Data for SG units

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SG1</th>
<th>SG2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_n$ [MVA]</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>$P_n$ [MW]</td>
<td>20</td>
<td>67.5</td>
</tr>
<tr>
<td>$U_n$ [kV]</td>
<td>10.5</td>
<td>10.5</td>
</tr>
<tr>
<td>$f$ [Hz]</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$T_a$ [s]</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>$R_a$ [p.u]</td>
<td>0.05</td>
<td>0.003</td>
</tr>
<tr>
<td>$X_{as}$ [p.u]</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$T_a''$ [s]</td>
<td>0.0538</td>
<td>0.05</td>
</tr>
<tr>
<td>$X_{d''}$ [p.u]</td>
<td>0.28</td>
<td>0.237</td>
</tr>
<tr>
<td>$T_d'$ [s]</td>
<td>0.19</td>
<td>1.62</td>
</tr>
<tr>
<td>$X_d'$ [p.u]</td>
<td>0.41</td>
<td>0.381</td>
</tr>
<tr>
<td>$X_d$ [p.u]</td>
<td>1.07</td>
<td>0.92</td>
</tr>
<tr>
<td>$T_q''$ [s]</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>$X_{q''}$ [p.u]</td>
<td>0.3154</td>
<td>0.252</td>
</tr>
<tr>
<td>$T_q'$ [s]</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$X_q'$ [p.u]</td>
<td>0.663</td>
<td>0.631</td>
</tr>
<tr>
<td>$X_q$ [p.u]</td>
<td>0.663</td>
<td>0.631</td>
</tr>
</tbody>
</table>

Figure 5.5 Model of EPS for black-start procedure
The first cranking path is comprised of synchronous generator SG1, step-up transformer TR1, transmission lines T_Line 1, T_Line 2 and transformer TR3. The second cranking path consists of synchronous generator SG2, step-up transformer TR2 and transmission lines T_Line 3 and T_Line 4. Each cranking path can be re-energized applying the previously tested methods in Chapter 4 section 4.2. The results that we obtained were similar as the ones presented in Chapter 4. Soft energization method was considered to be an appropriate method for re-energization of the separate cranking paths. After the establishment of the separate areas, namely we have two small electrical islands which should be synchronized in order to establish one larger electrical island. The model allows two re-energized islands to be synchronized at a certain location, as it is denoted in Figure 5.5. Both islands represent independent EPS; hence they had different frequencies and voltage magnitudes. Prior to synchronization of the areas it was necessary to bring the systems to a condition with stable frequency and voltage, then adjust the phase angle difference if necessary, depending on the momentary value. Figure 5.6 presents the synchronizer where we can see that the conditions for synchronization were not met. Lights were inserted to indicate which conditions are met and which are not. We see that the phase angle difference across the breaker was too large, specifically 178 degrees. The synchronizer allows synchronization once all of the conditions are met. By adjusting the torque of one machine, we were adjusting the phase angle until it reached value within the permitted range, in this case around 4 degrees (Figure 5.7). Finally, when all the checks were within the permitted range, the synchronizer allowed closure of the circuit breaker, which we can observe in Figure 5.7. Push button controls were used to give signals for closing the circuit breaker and opening the circuit breaker. We should also mention, that the operator can give closure command before the synchronization is allowed, however, the synchronization check relay will wait until the conditions for synchronization are met, and then will automatically close the breaker. In Figure 5.8 we see that the synchronization between the islands was successful. Figure 5.9 illustrates the monitored frequency of each electrical island during the synchronization.
Figure 5.6 Synchronizer – the conditions for synchronization are not met

Figure 5.7 Synchronizer – the conditions for synchronization are met
Figure 5.8 Synchronization between the individual re-energized areas

Figure 5.9 Monitored frequency during synchronization
The results showed successful synchronization of the individual re-energized electrical islands. In the final step of the restoration process the loads were restored in multi-step pickups. Using the sliders $P_{\text{load}}$ and $Q_{\text{load}}$ the user specifies the active and reactive power demand of the load.

5.4. Graphical User Interface for the black-start simulator

This thesis has been focusing not just on the academic side of the problem, but also, how to implement it in a powerful environment, so that it is possible to be used, for example as a training tool. The overall aim of this work was to develop real-time simulator for black-start process that would enable connection of actual (protection and control) equipment and streaming of PMU measurements in the future research. For that purpose, a model of two independent areas was designed, each supplied by a single synchronous machine. Up to now, the simulator is able to carry out initial steps in the entire process, as it was described in the previous chapters, starting from the generators run-up, then building an electrical island by connecting other elements, or alternatively, using the soft energization approach in re-energization process.

The interaction between the user and the simulator is through the GUI designed in RSCAD RunTime module, presented in Figure 5.10.
In the upper part of Figure 5.10, we can see simplified single line representation of the EPS model. The circuit breakers are operated manually with the switches placed near the elements. They are accompanied by light indicators for a better visualization when a specific element is active, or not. In the lower part of the interface in Figure 5.10 are placed control elements and plots, monitoring a variety of variables enabled in the model. Since the number of these elements is large, they are grouped in several subsystems as we can see in the lower left part of Figure 5.10. Specifically, the Synchronizer subsystem is active in this case. In continuation, are described the basic controls implemented in the interface.

The basic controls for the SG are presented in Figure 5.11. They include switches for lock/free mode and governor mode. The load reference is adjusted by $L_{ref}$ slider. The time slider and the pushbutton are used whenever we need to apply some additional torque for a specific time, for example during the process of synchronization, in order to adjust the phase angle.
Further, the speed controls are presented. Figure 5.12 contains the elements used to start-up the generator and control the speed, hence frequency. We use a switch control to select Manual or Automatic control. When “Manual” control is selected, we adjust the reference values using the slider controls for the angular speed in p.u values. If “Automatic” is selected, then we specify the time when we want to start increasing the speed (frequency) and a slider that defines the frequency change (in Hz) in one second.

Similarly, voltage is increased by using the Voltage reference slider in case when “Manual” is chosen. For the “Automatic” increase two sliders are used to specify the time range in which we want to increase the voltage.
Figure 5.13 Voltage controls
Chapter 6

6.1. Conclusion

To re-energize a transmission network after a blackout is technically a complex task that involves sequence of coordinated actions framework, which should be studied and, as far as possible, prepared in advance. The master thesis was focused on relevant items relating to re-energizing EPS components after a major blackout. The goal of this research was to develop a model for simulation of black-start process in the EPS. For that purpose, the RTDS simulator was used which operates in real-time allowing the user to test and validate the operation of the EPS under realistic conditions. The model was developed in RSCAD, which includes a variety of components for detailed modelling.

In the first phase of the development, we modelled a part of an EPS that was disconnected from the interconnected EPS and performed a dynamic analysis of black-start process based both on top-down and bottom-up principle. From a blackout condition, we re-energized the EPS using the classical sequential switching of each component. Applying sequential switching method, caused undesirable dynamic phenomena, which can lead to unsuccessful procedure. The evaluation of the dynamic model for the first scenario gave somewhat expected results for the electric phenomena during energization. What we did not expect at the beginning was the appearance of a series sympathetic interaction between transformers during re-energization. The results of the simulation showed that, not only the well-known inrush phenomenon is present, but it is possible to expect a series sympathetic inrush phenomenon between two transformers as well. In order to mitigate the specific dynamic behaviour during re-energization and the risk of failure of the procedure, TSOs are testing an alternative approach for re-energization, i.e. soft energization method. We attempted upgrading the existing EPS model for analysing the soft energization procedure on a real-time simulation. Hence, we modified the model in order to be able for soft energization approach and tested it, which gave a positive outcome for the feasibility of the method on a real-time computer simulation, specifically using the RTDS. Using the soft energization method instead of sequential switching mitigates the risk of transients and oscillations. Additional advantage is that small generators can be used to
re-establish the grid without causing problems in terms of re-energization of large transformers, which provides flexibility in the procedure.

Next, we added another part of the EPS with its own synchronous machine, establishing a second network path in islanded operation. Hence, the model allows investigation of the synchronization between the electrical islands. With the latest upgrades of the model, our aim was to get closer to an actual EPS configuration. Up to now, the model not only allows real-time simulation of different approaches for energization of the components, but also testing the impact of various factors, initial steps for incorporating loads, protection devices and fundamental requirements for synchronization of two re-energized areas.

Simulation results obtained for voltage and current profiles indicate that the shape and the amplitude of the variables depend on the connection instant, the modelling of the magnetizing characteristic and the assumption of the amount of residual magnetism in the transformers. It can be concluded that for such black-start process, detailed information are needed for the components in the model in order to achieve a satisfactory correspondence to a possible live test of unit’s black-start capability. More often, this type of data collection can be time-consuming and quite difficult or too complex to collect. Nevertheless, we consider the developed simulator as a good tool for analysing the black-start procedure for education purposes, as well as training for operators.

6.2. Outlook

Using the RTDS device for testing of a black-start procedure enables a wide range of simulations under various operating conditions, furthermore a possibility of testing a real physical power equipment operation during black-start procedure. Various possibilities are open for future research on this topic. Further research in this area can may be focused on improving the model for more accurate results. With the latest model upgrades, our goal is to get closer to the actual process by including actual protective devices and eventually developing a complete training simulator for education and operator’s training purposes. PMU streaming from actual EPS might be incorporated to the RTDS model in order to enable performing parallel actions in the model and the real EPS and in this way verify the feasibility of each manipulation in advance.
References


[23] RTDS Technologies, RTDS Tutorial.


