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Article

Power system restoration protocol for planned events in a real time simulator

Protocolo de restauración de un sistema eléctrico para eventos planeados en un simulador en tiempo real

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Abstract

This work presents the analysis of planned events in an electrical power network to establish the optimal system restoration protocol for recovering an electrical system. First, a technical description of each maneuver is provided, along with the operational protocol that is followed to decide whether or not it is feasible to carry it out. Once the decision is made to proceed, the preparation of the electrical network is demonstrated. To ensure that all those involved in the technical operational aspect follow a standard reconnection procedure, each event is simulated in the simulator, and the restoration sequence chosen by the person being evaluated is analyzed to determine whether the sequence followed is appropriate or if any specific steps could have been avoided and/or modified. Finally, an assessment is made to determine whether the person being evaluated is ready to operate the network live or if they need more training hours on the simulator. In this way, the simulator becomes an additional tool to the one-on-one teaching that is passed from an operator to their assistant until the latter is capable of operating the network on their own.

Objetives	Methodology	Contributions
Analysis of the elements of the electrical power system. **Analysis of the general conditions of the power system.** **Analysis of the operation of the power system in view of planned events.** **Analysis of the operation of the power system in view of planned events.** **Analysis of the abnormal operation regime facing intentional events.**	**Follows the next steps:** **Element restoration sequence.** **Voltage and frequency control during a planned maneuver.** **Restoration maneuvers.**	**Training performs all restoration maneuvers, in the simulator, correctly; this does not indicate that you are already 100% trained to operate on the live network because stress management is different knowing that if you make a mistake nothing really happens.** **Testing real events to compare what an operator did under stress with what even the same operator would do in a more controlled environment such as real-time simulation.**

Real time simulator, Power system restoration, Connecting and disconnecting protocol

Resumen

Este trabajo presenta el análisis de los eventos planeados en una red eléctrica de potencia para establecer el protocolo de restablecimiento óptimo de recuperación del sistema eléctrico. Primero se hace una descripción técnica de cada maniobra y el protocolo operativo que se sigue para decidir si es factible o no llevarla a cabo; una vez que se toma la decisión de llevarla a cabo, se muestra como se prepara la red eléctrica. A fin de que todos los involucrados en la parte técnica operativa sigan un estándar de reconexión, se simula cada evento en el simulador y se analiza la secuencia de restablecimiento que elige la persona que se está evaluando para después analizar si la secuencia que se siguió es adecuada o si se pudo evitar y/o modificar algún paso especifico. Finalmente se califica si la persona que se está evaluando ya está en condiciones de operar la red en vivo o si necesita más horas de capacitación en el simulador. El simulador así se vuelve una herramienta adicional a la enseñanza uno a uno que se transmite de un operador a su ayudante hasta que esté está en condiciones de operar la red por sí mismo.

Objetivos	Metodología	Contribuciones
Análisis de los elementos del sistema de energía eléctrica. **Análisis de las condiciones generales del sistema eléctrico.** **Análisis del funcionamiento del sistema eléctrico ante eventos planificados.** **Análisis del funcionamiento del sistema eléctrico ante eventos planificados.** **Análisis del régimen de operación anormal ante eventos intencionales.**	**Sigue los siguientes pasos:** **Secuencia de restauración de elementos.** **Control de tensión y frecuencia durante una maniobra planificada.** **Maniobras de restauración.**	**El entrenamiento realiza correctamente todas las maniobras de restauración, en el simulador; esto no indica que ya estés 100% capacitado para operar en la red en vivo porque el manejo del estrés es diferente sabiendo que si te equivocas realmente no pasa nada.** **Probar eventos reales para comparar lo que hizo un operador bajo estrés con lo que haría incluso el mismo operador en un entorno más controlado, como una simulación en tiempo real.**

Simulación tiempo real, Restauración de sistemas de potencia, Protocolo de conexión y desconexión

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Introduction

Since electrical systems are constantly changing, and the components of a network, as well as their control systems, adapt to modern times, the planning strategies adopted by each control center also evolve, allowing for the continuous development of procedures, rules, tests, and experiences that describe the operating philosophy of electrical systems (Official journal of the federation). In the daily operation of an electrical system, the focus is on maintaining power quality parameters, such as voltage level and frequency. As part of this operation, scheduled maintenance work is coordinated, always ensuring the system's safety.

Despite these precautions and the continuous monitoring of the electrical system, disturbances occur unpredictably, leading to the loss of a network element, a section, or the entire system. As a result, a protocol for disconnecting and restoring elements is followed as part of the routine tasks of a network operator. During the brief period of a planned disconnection, the operator is simply an observer. However, once the event occurs, the operator is left with a section of the network in an unbalanced state. Thus, the operator's primary task is to bring the electrical system from this point to full recovery, relying on their knowledge and skill to execute manoeuvres that restore the system while staying within operational limits (Jacob, R. A. et.al.).

Although all control centers are committed to the continuous training of their personnel, the lack of a detailed description of the steps to follow for system recovery after a disturbance—whether or not it results from a planned event—places this responsibility on the operator in charge. However, the person on duty must have the ability not only to restore the system but to do so reliably and in the shortest possible time.

Currently, one of the most efficient testing protocols is based on real-time simulators in their different forms, that is, using the closed loop between two simulated systems (software in the loop - SIL), creating the interface between two physical elements that they simulate (hardware in the loop - HIL), or by creating the interface between a device and the computer (Rapid control prototyping - RCP).

Among the most common or well-known simulators are RTDS (Real Time Digital Simulator) and E-MegaSym Real Time. Both have the versatility to simulate in the three ways previously stated. Another strategy is the one used in personnel training, where simulators are used that emulate specific events and the person to be trained interacts with said simulator.

The best known are flight simulators and/or some that are even used as part of a hobby or fun, such as simulators to drive anything from a simple element like a bicycle to something complex like a combat helicopter. Of course, the closer the virtual reproduction is to reality, the better the training is or rather the more effective this training will be because the interaction between the person and the machine is practically real, that is, it requires the person to perform the necessary same movements and subjects it to the same stress as if it were a real event (Krpan, M. et.al).

The National Energy Control Center (CENACE) in Mexico uses a simulator called ORACLE, this simulator has the energy network and updates it from time to time. In it, phenomena or events can be reproduced, whether past (real), or fictitious by programming them. Additionally, the state of the network can be monitored in real time. The events for training, whether real or fictitious, develop at the speed and in the sequence in which they would physically occur, in such a way that by being able to interact with the system, the measures or decisions taken will lead to the recovery of the system or its destruction collapse; this is the way in which the personnel to be trained are tested without putting the system at risk but emulating the state of both the network and the environment that surrounds it.

For this to happen, the personnel dedicated to training know perfectly well what they must do to recover the network, however, since the sequence of maneuvers to bring the network to a new stable state is not unique, only the performance can be evaluated of personnel to be trained until the entire operation has been completed.

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It is the case, when there are past events, where a network operator made all the maneuvers for recovery, that in the simulator are emulated as if they happened again with such precision that if the same sequence of maneuvers is followed, it is recovered in virtual form the network; however, different sequences can be tested to evaluate if the most appropriate was done since the energization sequence can result in both users and energy generation companies not being operational for a period of time (second, minutes or more) that is translates to economic losses. Although in the strict sense, since there is no restoration protocol, since the events in a network are n-exponential, network operators in a state of stress at the limit are trusted to do the best they can for the condition they have (Wu, H. et.al) and (Verma, S. & Chelliah, T. R.).

Elements of the electrical power system

From an operational point of view, it can be considered that the most important elements are the generators, lines, transformers, switches and loads. Below is a technical description of the limitations of each of these elements.

Operating limit of a generating unit

Generating units play an important role in the electrical power system, not only because of their generation, but also because of their ability to control voltage levels in nodes or important areas surrounding them. The generators are dispatched according to their fuel availability, whether fossil fuel, gas, water, etc. In addition to environmental and social conditions, for example, the pollution associated with thermoelectric plants and the impact of using or not using hydraulic units when dams have high or low reservoir levels. Thermoelectric units are generally dispatched at their maximum capacity, although the trend is to change to combined cycle units, which are very efficient units with very little environmental pollution. Generators cannot take maximum load instantly, this limits their operation according to their power and type, for example: for a hydroelectric generating unit, its load taking depends greatly on its type of turbine, as well as its generator, but for a common 320 MW hydroelectric generator it will take 25 MW per minute for the first 2 approximately and increases until it takes 60 or 70 MW/min for the next 5 minutes until it reaches its maximum value or the one requested.

On the other hand, in the case of a thermoelectric generator its load taking capacity at start-up is very slow compared to a hydroelectric generator, this for example starts with just 5 MW/min and can reach 10 MW/min for more efficient machines; so, they take a long time to reach their maximum level.

Operating limit of a transformer

A power transformer has a typical flux-current magnetization curve as shown in Figure 1. To avoid having so many losses, it works below the inflection point indicated in this figure with the intercept of the dotted lines, that is, in its linear and most efficient area. Figure 1 clearly shows that from that point on, the current can be increased considerably but the concatenated flux increases very little, for this reason the transformer is limited to working outside that zone.

Box 1

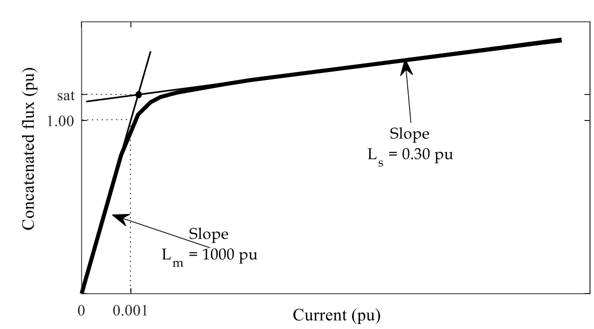

Figure 1
Magnetization curve of flux-current for a power transformer

Source: Own elaboration

The two main causes of surges due to transformer connection/disconnection are transformer energization and the effect of load rejection, both events are described below.

Energization

When a transformer is energized, a large amount of harmonic-rich inrush current can flow, which depends mainly on the point of the voltage wave applied to the transformer at the instant of energization, the remaining flux of the transformer, and its reactance air core. Transformer voltage waveforms for a representative case are found in figure 2.

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Figure 3 shows a harmonic analysis over time for phase A of the inrush current; the others behave in a similar way. It is observed that the inrush current has a high second harmonic content in addition to its fundamental and dc component; third, fourth and fifth harmonic components with considerable amplitude are also generated.

Box 2

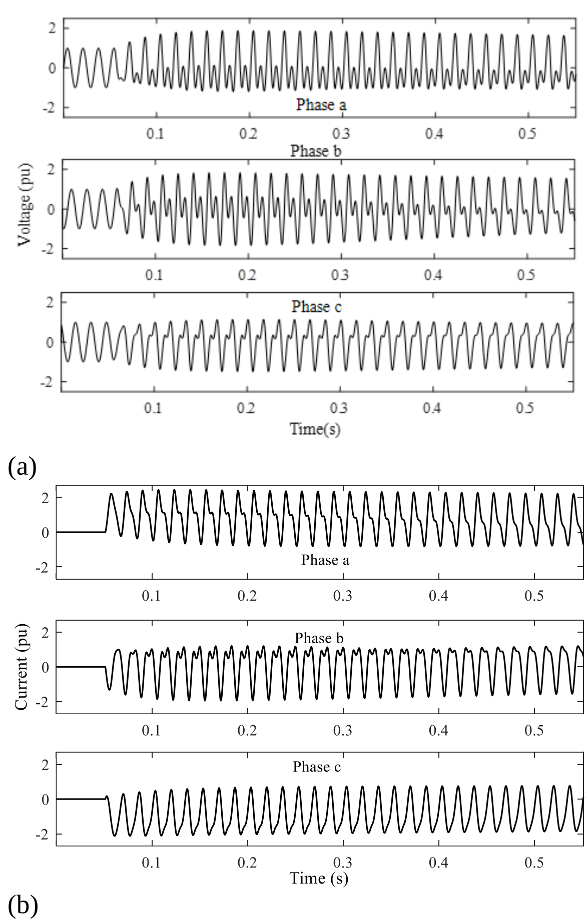

Figure 2
Voltage and current waveforms during the energization of a 500 MVA transformer in a system with an inrush current of 2.5 kA: (a) Currents, (b) overvoltages at the transformer terminals.

Source: Own elaboration

Box 3

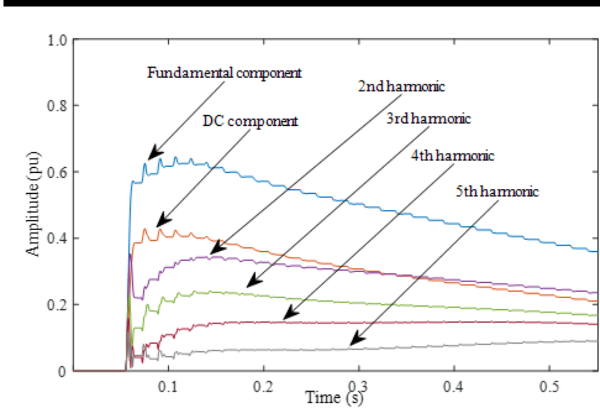

Figure 3
Harmonic components of the inrush currents for phase a

Source: Own elaboration

Load rejection

When a load at the end of a transmission line is disconnected, it generates excess reactive power, leading to temporary surges in the electrical system. These surges depend on the short-circuit power at the load connection point, the magnitude of the rejected load, and the reactive power of the line, which in turn depends on the line parameters. The analysis of these over voltages is especially important if resonance effects occur due to the interaction of capacitive elements and inductive elements with a non-linear characteristic (Das, J. C.) and (IEC/IEC 60099-5). In general, a system with relatively short lines and high short circuit power will have low surge voltages, while a system with long lines and low short circuit power will have high surge voltages (Das, J. C.) and (IEC/IEC 60099-5). The time these surges last depends on the type of generators (Das, J. C.), (IEC/IEC 60099-5) and (CIGRE Working group 06). Since the voltage at the receiving end of the line is kept at 1 pu, the voltage behind the equivalent impedance of the system increases with the load current, which is directly proportional to the load power. Thus, since the source voltage is proportional to the load, the larger the connected load, the greater the surge voltages are expected to occur. The zero-sequence impedance has an influence on over voltages due to the different opening times of the switches, and this influence is marked in the first moments of disconnection. Therefore, for a system with a higher zero sequence impedance the surges are higher.

Operating limit of a transmission line

The two operational limits that exist within transmission lines are the energy transmitted (MVA) or the amperes. There is a limitation of the MVA's due to the construction of the line itself (avoid heating) or in other cases due to lines with long line classification, due to stability margin (Sybille, G.). The other limitation (amperes) is due to the measurement capacity of the primary equipment (current transformers). When the network is in normal conditions, due to the effects of the load zones and network topology, when any link tends to be overloaded, CENAL makes the decision to modify the generation or open lines as appropriate. When the network is already in a stressed condition, the operator reviews its flows in real time and upon observing an overloaded line, tries to resolve it, making the decision to modify the network by opening or closing transmission lines.

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Opening and closing switches

The switches are mechanical systems that disconnect the elements of the SEP, although they have an action time of a few milliseconds, for the purpose of planned maneuvers they do not cause any additional problem to the SEP, for this reason within the connection/disconnection protocol they are considered passive elements, that is, with ideal performance.

General conditions of the power system

An electrical power system serves as a means of transport for energy but cannot store it, for this reason there must be a balance between generation and load at all times.

Naturally, if the load is at the maximum generation limit and in addition the lines are transporting the maximum amount of energy they support, the system is at a point where even a planned maneuver can trigger a sequence where it can be a general collapse.

The operational constraints of generation, transmission, transformation and design are associated with steady state limitations, transient stability (angular), transient voltage stability and long-term stability; characterized by maximum and minimum limits.

Box 4

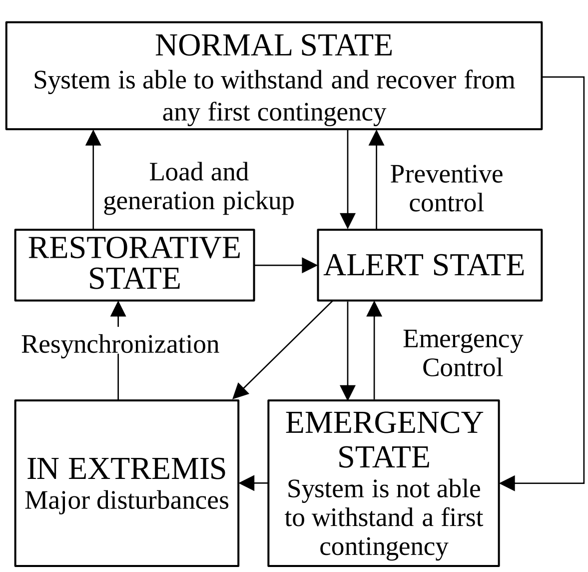

Figure 4
PES states

Source: Own elaboration

Operating states of the electrical power system

Due to the dynamics that exist between the different members of the electrical industry and the general restrictions or limitations (operational and design) that may be present when operating the national electric system (NES), which implies operating outside of operational, reactive reserve, voltage levels, transmission and transformation capacity among others, four operational states were established. As a consequence of the set of restrictions, five operating states can be identified as shown in figure 4, each of them is described below.

Normal state. - In this state, the electrical system operates with sufficient reserve margins in generation, transmission and transformation, to comply with the concept of security in the event of possible simple contingencies that may arise. Post-contingency, the electrical equipment must remain operating within its permissible limits, both operational and design, and must not present a loss of charge.

Alert state. - In the alert operating state, all the variables of the NES are still within their operational limits, however, in the event of a contingency, the NES can continue to be stable without the action of the supplementary control schemes or, it can lead to the emergency operating state in which the system is at potential risk of instability.

Emergency operating state. - In this state, it operates below the established reserve limits. Equipment operates outside its operating and design limits. Load affectation either by the operation of a protection scheme or manual load pull. In this state, the occurrence of a more severe simple contingency will lead the NES to a condition of instability and operation in this state requires the execution of remedial actions.

Restorative state. - The electrical islands that remain active will supply a part of the total demand with the equipment operating within its design limits. In this state, all control efforts must be focused on reintegrating the system and supplying the total demand in the shortest possible time.

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Operating characteristics of a generating plants

In the normal operating state, to achieve reliable operation of the electrical system in the load-generation balance, a reserve of rolling and cold generation is required available at any time to maintain the frequency in the programmed quality band, satisfy variations in demand and avoid affecting the load and operation of the turbo generators outside the design limits.

Before a planned maneuver, each control area must identify strategic generating plants contemplated in the restoration plans in the event of a general or partial collapse in which the installation is required (if it is not available) of the necessary equipment to have the "black startup" capacity. This guarantees the supply and quality of energy in the event of the most severe simple contingency after the planned maneuver.

Operation of the power system in view of planned events

A planned event has an economic cost and an operational cost, each of them is evaluated in order to decide if the maneuver is feasible and safe, a brief description of both is provided in the following paragraph.

According to available resources

The resources available largely dictate whether a planned operation can be carried out or not, the protocol to follow is described below:

1. The need for preventive/corrective maintenance, commissioning or modifications is detected and the request is made to CENACE.

2. They send license applications to CENACE for evaluation and authorization, complying with the established requirements. A registration number is assigned to the request.

3. CENACE carries out the preliminary evaluation of the license application in the requested scenario, in its area of responsibility.

4. CENACE carries out the first contingency security analysis on the network associated with the license request.

5. If feasible, CENACE authorizes the license application under the required conditions, notifying the applicant.

6. If it is not feasible to authorize the application, CENACE reschedules the application, in common agreement with the applicant. If an agreement is not reached, the application is canceled and the applicant must apply for a new application.

7. The applicant defines the moment in which they are prepared to start live or dead work that requires taking the equipment out of service and/or requesting to initiate a maneuver from the control center.

8. The applicant verifies previous operating conditions and requests from the CENACE operator authorization to begin executing the maneuver associated with the request, whether scheduled or emergency.

9. CENACE evaluates and adjusts the operational conditions required to execute the maneuvers associated with the scheduled or emergency request. If the above is not possible, the application is rescheduled and/or canceled with the proper justification established in the license application.

10. Prior to starting a maneuver, CENACE will deliver a license to the applicant and authorize the execution of maneuvers associated with the request. If necessary, CENACE will coordinate the execution of the maneuver.

11. Execute the maneuvers to release the equipment requested in the license. They record the schedules of each of them.

12. The applicant notifies the CENACE operator of the end of the maneuvers.

13. The applicant reports the completion of the work, and requests authorization to begin a maneuver to normalize the licensed equipment.

14. CENACE confirms completed work and withdraws the license.

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15. CENACE verifies and adjusts the operating conditions necessary for the standardization of the equipment, and authorizes the execution of maneuvers or, where appropriate, indicates from what time the maneuvers can be carried out.

16. The applicant normalizes the equipment by executing the maneuvers according to the maneuver catalog.

According to the operating cost

Each element of an electrical network has a weight in the stability and control of said network; this weight can be measured with a sensitivity study and will depend on the network connectivity. For this reason, disconnecting equipment has a different impact (operating cost) depending on the state of the network. In this way, operators heuristically evaluate the risk of disconnecting equipment for maintenance; this evaluation is supported by contingency studies to verify if the network supports the disconnection of said equipment, however the impact of this disconnection can only be evaluated by the operator on duty in such a way that he has to decide what is the most appropriate moment (of lesser impact) to make the release. There are emergency maneuvers that must be carried out at the moment they are requested by people from other departments, even so if the operator on duty determines that it is not feasible, it is agreed with the others involved to carry it out as soon as possible depending on the situation equipment failure.

Abnormal operation regime facing intentional events

The 5 fundamental elements in an electrical power system are the lines, the generators, the transformers, the switches and the loads. In general terms, each element is disconnected and/or connected according to the arrangement of switches available, so when It is necessary, whether due to maintenance or failure, to disconnect and/or connect some SEP equipment, a sequence must be followed for each element, coordinated in real time by the SEP operator and verified at all times, in each substation. by its operator. The oscillations that the maneuver may cause are monitored at all times by the operator; In the event of a contingency or abnormality in the network, he will have to decide, immediately, to continue or suspend the maneuver.

Output sequence of a SEP element

LINE: To carry out the programmed disconnection of a transmission line, the steps may vary according to the switch arrangement, for example, in the case of a simple switch, the following steps are followed:

1. The first maneuver is to deenergize the line using the switches that can extinguish the electric arc that may occur. In this step it is important to decide in which substation to open the line first, since for a few minutes there will be an empty line, which generates reagents causing a rise in the voltage to which it is still connected.

2. The blades at both ends of the line are opened.

3. Both ends of the line are grounded using blades to de-energize it. This completes the disconnection maneuver of a transmission line.

GENERATOR: When a generator needs to be disconnected, the power plant operator must give a stop pulse to the generator. With this pulse, the first thing he does is open the machine switch. When this happens, he begins to stop the rotor. When this ends, own services begin to be disconnected and finally some generators are grounded.

TRANSFORMER: As in the lines, the disconnection maneuver of a transformer is based on the arrangement of switches that it has, for example, for a simple switch the following sequence of maneuvers is followed:

1. The switch on the low voltage side is opened because the current reflections for the high voltage side will be of lower magnitude, and the electric arc on the low voltage side will be of lower amplitude.

2. The high voltage switch opens.

3. The blades of both switches are disconnected. This concludes the disconnection sequence of a power transformer.

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SWITCH: The procedure to de-energize a switch varies according to the arrangement of switches that are used, the most common is to transfer the load that the switch that is to be de-energized is taking to another switch called "wildcard", the procedure is as follows:

1. The "wildcard" switch blades are closed (which should normally be open as well as the switch), as well as the transfer blade of the switch that will be de-energized is closed.

2. The "wildcard" switch is closed, after which the switch that will be released is opened. It is worth mentioning that when the transfer blade in step 1 is closed, the switches own protections are transferred to the "wild card" switch.

3. Finally, only the switch blades are opened to complete the de-energization. In the case of a double or half switch arrangement, it will be enough to open the switch as well as its side blades.

LOAD: In emergency conditions of the National Electrical System, the only one authorized to disconnect load is the National Energy Center. There are several types of cargo, among them the so-called Interruptible Cargo, which is cargo that can be interrupted totally or partially in accordance with the provisions of the current rates. In times of emergency, the load pull is the last resort that should be taken by the operators, but in the case of a planned load pull, it must be announced to the interested party days in advance. It will be enough to open switches or blades under load in the control area.

Element restoration sequence

LINE: To restore a transmission line, the steps may vary, as in the case of disconnection, according to the arrangement of switches, for example, in the case of a simple switch, the following steps are followed:

1. As a first step, you must remove all physical soil as well as open the ground blades.

2. Next, the blades are closed at both ends of the line.

3. You must choose which node the switch closes first, taking into account its electrical robustness since there will be a line empty for a moment of time or in another case you may have a line with a fault or some element. ashore. Afterwards, the other switch is closed, having already an energized line. This completes the connection maneuver of a transmission line.

GENERATOR: It begins with reestablishing all the generator services. The generator begins to run, and upon reaching the plate RPM, synchronization with the National Electrical System is carried out through the machine switch.

TRANSFORMER: As in the lines, the energization maneuver of a transformer is based on the arrangement of switches that it has, for example, for a simple switch the following sequence of maneuvers is followed:

1. It is verified that all the switches associated with the transformer are open, once this the blades of the switches are closed.

2. The high voltage switch is closed.

3. The low voltage switch is closed. This concludes the energization sequence of a power transformer.

SWITCH: The procedure to energize a switch that is used as a wildcard switch is as follows:

1. For safety reasons, it is verified that after work the switch has been left open, once this is confirmed, the switch's own blades are closed.

2. The switch is closed.

3. The "wildcard" switch opens. Once open, its side blades open as well as the so-called transfer blade of the switch that was energized.

LOAD: To restore the disconnected load, it is enough to command the closure of the switch from the control room, as in the case of a knife under load, if you have control in the room, or do it from the substation panel.

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Voltage and frequency control during a planned maneuver

To guarantee reliable and safe operation of the interconnected system, the control zones in coordination with CeNal must control the generation, supply and administration of reactive power resources. The system must be operated with an adequate voltage profile and maintain a sufficient reactive power reserve margin in generation sources and static VAR compensators, in such a way that in the event of the most severe simple contingency, after a planned maneuver, the system is stable. In the event of contingencies due to a planned event, the supply of reactive power must be automatic; manual actions to support and control the network voltage profile are not recommended. Before a maneuver, to guarantee that the supply and quality of the energy will not be lost, it is monitored that:

1. The transmission lines are in service and can only be disconnected for voltage control if electrical studies show that the reliability of the system does not degrade significantly.

2. It is necessary that the reactors and banks of shunt capacitors be provided with switches to avoid de-energizing other facilities, when it is required to connect or disconnect them for voltage control.

3. All generating units must have the capacity to generate/absorb reactive power according to their capability face. Likewise, be equipped with automatic voltage control equipment and operated in this control mode for as long as possible.

Analysis of recovery events

The simulator has the function of emulating PES events in such a way that the recreation of these events serves to follow the performance of a person virtually operating the network. Possible events and/or events that have already occurred in the electrical system are proposed. This simulator has the peculiarity that it has the network diagram so that past events can be simulated and verify if the live maneuvers were the most appropriate to recover the network, in this way not only the personnel are trained but also verifies the efficiency and effectiveness of the operators.

Figure 5 shows the test network used in the real-time simulator, this network is similar to the real network in the western area of México, where operators and/or future network operators are trained. Below is a description of events and the maneuvers that the person in training followed to recover the network. In this network, the event to be simulated is associated with an average load similar to that of a normal day of operation. The simulator takes this data directly from the real network and is simply saved in a file that can later be recovered in the simulator to do the training.

Event B6 AT-04

The network condition is that all flows from nodes marked as generation are incoming except those marked with B71 and B36. In this condition, the simulator operator generates a fault in one of the two transformers (AT-02) of the substation marked as B6, immediately leaving the other transformer marked as AT-03 at 138% of its nominal capacity. It should be noted that the load and generations of the network are kept intact, and only the necessary maneuvers need to be made to reorient the flows.

Restoration maneuvers

The person who is in the simulator and is training must do all the maneuvers to recover the adequate condition of the network. The maneuvers they perform will immediately affect the network, just as would happen if they were operating it live; this person performs the following reset sequence.

1. Open the switch (marked with 1 in an orange box) of one of the lines that goes from B6 to B56 to transfer part of the load from B6 to B66, with this maneuver the AT-03 transformer of the substation B6 drops to 134% of its nominal capacity.

2. Open the switch (marked with 2 in an orange box) of the other line that goes to B66 (line B6-B56) to transfer that part of the load to the B66 substation, with this maneuver the AT-03 transformer drops to 127% of its nominal capacity.

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3. Open the switch (marked with 3 in an orange box) of the line that goes from B52 to B44 and thus load is transferred to substations B2 and B5; with this maneuver, the flows are redirected and the condition of the network is as follows: AT-03 is at 90% of its nominal capacity, B2 at 76% of its nominal capacity, and B5 with overload at 113% of its nominal capacity. nominal capacity.

4. Open the switch (marked with 4 in an orange box) of the line that goes to B36 to discharge B5 in such a way that in the reorientation of flows no transformer remains above its nominal capacity, thus recovering the condition adequate network 100%.

Box 5

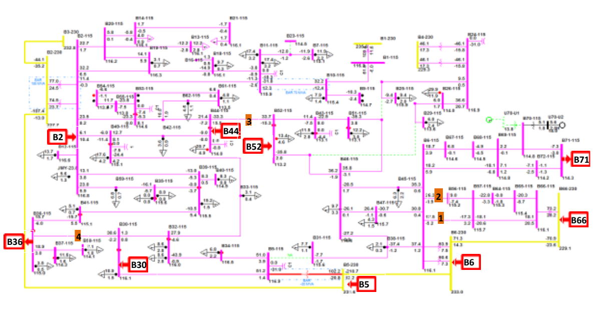

Figure 5
Network used in the real-time simulator for event AT-02 of substation B1

Source: Own elaboration

Event B6 AT-03

The 230 kV and 115 kV electrical network shown in figure 6 is in normal operating conditions. It is proposed to recreate a real event in the simulator. On the day of the event, there were no reports of rain or strong winds in the area; The load of the transformers was as follows: B6-AT-01 at 83%, B6 AT-02 at 86%, B5 at 101%, B66 at 63%, B2 AT-01 at 87% and B2 AT- 02 at 84%. At 16:59 on the day in question, the switches connected to B6 AT-03 trip, due to the operation of protections 86 and 87 (differential and overcurrent relay respectively). In the event, the low side of B6 AT-04 trips due to protection operation 51.

The disturbance affects 23.5 MW due to operation of the low voltage protection scheme (27's – low voltage relay) by tripping the low side of the transformers of the following substations: B43, B67 and B69 when voltages of 102 kV are present.

The event is recreated in the real-time simulator for training purposes; The person conducting the training makes all the disconnections simulating the operation of the relays. In this way, the real conditions of the event are obtained and from there the restoration begins. The person to be trained performs the following maneuvers to recover the network.

Restoration maneuvers

The person who is in the simulator and is training must do all the maneuvers to recover the adequate condition of the network, the final conditions after the event are: B66 at 127%, B5 at 124% and B2 at 120%. The flow of the line from B44 to B52 is 33 MW and the flow from B57 to B6 is 65 MW. As a B6 AT-04 overload trip (160%) and 23.5 MW were affected by operation of the 27's; several maneuvers can be done such as: closing IN-72040 in B6, pulling load to be sure that when closing B6 AT-04 it will not trip again due to overload, or trying to restore the affected load before putting B6 AT-04 into service. The trainee performs the following reset sequence.

1. Closes IN-72040 in B6 (marked with 1 in an orange box) leaving AT-04 with an overload of 130%, in S.E B66 AT-01 remains with 72%, in S.E B5 AT-01 with 108 % and the S.E B2 AT-01 and AT-02 with 88%.

2. To unload in the S.E B6 AT-04, the 115 kV network is disconnected, the operator opens the switch (marked with 2 in an orange box) of one of the lines that goes from B6 to B57 with this maneuver. AT-04 transformer presents 122% overload.

3. Operator opens the switch (marked with 3 in an orange box) of the line that goes from B6 to B56 in the B6 substation, with this maneuver the B6 AT-04 transformer is left with a 105% overload, modifying the B66 loading to 92%.

4. If the affected load is restored in this condition, B6 AT-04 would be overloaded again with tripping possibilities, therefore, the operator opens the switch (marked with 4 in an orange box) of the line that goes from B52 to B44 at substation B52. With this maneuver, the transformers are loaded as follows: B6 AT-04 73%, B66 92%, B5 117% and B2 94%.

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5. With the previous maneuver, the S.E B5 AT-01 was overloaded with 117% of nominal capacity. Operator opens the switch (marked with 5 in an orange box) of line B30-B36 of substation B30 in order to discharge B5. The transformers are as follows: B6 AT-04 73%, B66 AT 01 with 92%, in S.E B5 AT-01 with 104% and S.E B2 AT-01, 02 at 100%.

6. The load affected by the operation of protection 27 is restored, the final state of the transformers is: B6 AT-04 99%, B66 AT-01 at 92%, in B5 AT-01 at 104% and in B2 AT01, 02 at 100%.

Box 6

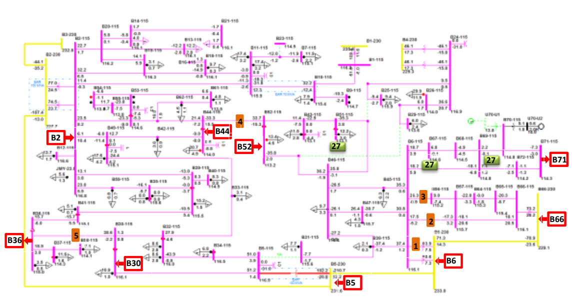

Figure 6
Network used in the real-time simulator for event AT-03 of substation B6

Source: Own elaboration

Event B5 AT-01

The 230 kV and 115 kV electrical network shown in figure 7 is in normal operating conditions. It is proposed to recreate a real event in the simulator. On the day of the event, there were no reports of rain or strong winds in the area; The load on the transformers was as follows: B6-AT-03 at 83%, B6 AT-04 at 86%, B5 AT-01 at 101%, B66 AT-01 at 63%, B2 AT-01 at 87% and B2 AT-02 at 84%. The person doing the training operates protection 86 and 87 of transformer B5 AT-01, this indicates that this transformer goes out of service and cannot be recovered. Due to the disturbance, the operation of the system protection scheme due to low voltage (27's) is affected by tripping the low side of the B34 substation transformer when voltages of 103 kV are present. With the disturbance, the load on the transformers remains as follows: B6-AT-03 at 89%, B6 AT-04 at 92%, B5 AT-01 at 0%, B66 AT-01 at 65%, B2 AT- 01 at 121% and B2 AT-02 at 117%.

Restoration maneuvers

The person who is in the simulator and is training must do all the maneuvers to recover the proper condition of the network by performing the following restoration sequence.

1. Open the switch (marked with 1 in an orange box) from line B46 to B38 on B46. This maneuver prepares the network for the next one. This maneuver is to avoid overloading the line from B6 to B38 with the closure of the switch (marked with 4 in an orange box) on S.E B31.

2. Open the switch (marked with 2 in an orange box) from line B6 to B56 in B6, with this maneuver the flux in the transformers is: B6-AT-03 at 80%, B6 AT-04 at 83%, B5 AT-01 at 0%, B66 AT-01 at 74 %, B2 AT-01 at 124% and B2 AT-02 at 120%. With this maneuver the network is prepared so as not to overload the AT in B6.

3. Open the switch (marked with 3 in an orange box) from line B6 to B57 in B6, with this maneuver the flux in the transformers is: B6-AT-03 at 69%, B6 AT-04 at 71%, B5 AT-01 at 0%, B66 AT-01 at 90% %, B2 AT-01 at 123% and B2 AT-02 at 119%. With this maneuver the network is prepared so as not to overload the AT in B6.

4. Close the switch (marked with 4 in an orange box) from line B31 to B5 at substation B31. With this maneuver, the direction of the flows is changed by reorienting a part that left B6 to substation B5. With this, the transformers are charged as follows: B6 AT-01 at 93%, B6 AT-02 at 96%, B5 AT-01 at 0%, B66 AT-01 at 90%, B2 AT-01 at 100% and B2 AT-02 at 98%.

5. The load affected by the operation of relays 27's of substation B34 is restored, leaving the load on the transformers as follows: B6-AT-03 at 97%, B6 AT-04 at 100%, B5 at 0%, B66 at 90%, B2 AT-01 at 104% and B2 AT-02 at 100%.

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Box 7

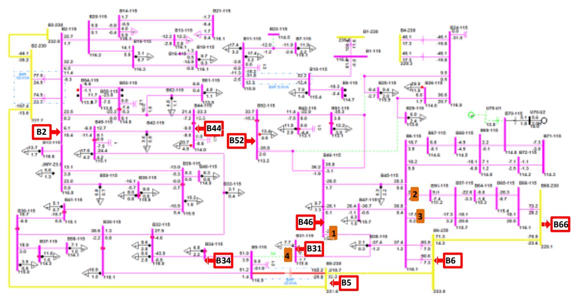

Figure 7
Network used in the real-time simulator for event AT-02 of substation B1

Source: Own elaboration

Conclusions

Normally the passing of knowledge one by one and acquiring experience in the field is what leads operators to be able to respond instantly in any operating condition; however, one strategy is training in real-time simulators that emulate the network. In this sense, the following was found:

1) The simulator is an appropriate tool to acquire skills in network operation.

2) When a person in training performs all restoration maneuvers, in the simulator, correctly; this does not indicate that you are already 100% trained to operate on the live network because stress management is different knowing that if you make a mistake nothing really happens.

3) However, if the person in training cannot correctly perform the appropriate maneuvers to restore the network, this does indicate that the person is not yet qualified to operate live regardless of his or her ability to handle stress.

4) By testing real events, you can compare what an operator did under stress with what even the same operator would do in a more controlled environment such as real-time simulation.

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Galván-Sánchez, V. A.: Wrote the article.

Gutiérrez-Robles, J. A.: Development the simulations y made the figures for the article.

Ortiz-Muro, V. H.: Review, generate and selection of the examples and/or results presented in the article.

Lopez-DeAlba, C. A.: Review of the content and putting the article into format.

Availability of data and materials

All the results that are obtained are in the article and can be accessed freely depending on the journal's policies.

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Abbreviations

CENACE	The National Energy Control Center
CENAL	National Control Center
EPS	Electrical Power System
HIL	Hardware In The Loop
MVA	Mega Volts Ampere
MW	Mega-Watts
NES	National Electric System
ORACLE	Company specialized in the developed of cloud and local solutions
RCP	Rapid Control Prototyping
RTDS	Real Time Digital Simulator
SIL	Software In The Loop

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