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CIGRE US National Committee
2017 Grid of the Future Symposium

Application of RTDS as Real-Time Decision Support Tool

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SUMMARY

Today power grids are being pushed to their operating limits. In addition, with higher penetration of intermittent renewable energy, operating power grids is becoming even more challenging. To have reliable power grid operation, a good decision support tool is needed. Traditionally, steady state analysis and eletro-mechnical dynamic simulation are used. However, these tools are not enough for the future power system because of much complicated dynamic interaction among many new components with different dynamic time constants. Therefore, an electromagnetic transient simulation tool is required to investigate the dynamic response of power grids in greater detail. However, to run the detailed electromagnetic transient simulation takes time. Sometimes it is not practical to serve as the supporting tool for real-time operations. Most of the time, only off-line studies can be performed. To perform real-time electromagnetic transient simulation requires significant computational power, such as the Real-Time Digital Simulator (RTDS), which Dominion Energy uses to support its real-time electric grid operations. In this paper, we will use two examples, remedial action scheme (RAS) and black start, to show how to use RTDS as a real-time decision support tool for system operators in Dominion Energy.

KEYWORDS

Real-time simulation, Remedial Action Scheme, Blackstart

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Introduction

Because of numerous reasons, such as deregulation, slow expansion of transmission line, and retirement of traditional power plants, power grids are pushed to their operating limits. In addition, with increasing penetration level of intermittent renewable resources, operating power grids is becoming even more challenging. Moreover, with higher frequency of severe weather, power grids will experience numerous contingencies and wide-spread blackout. In order to operate power grids reliably under such demanding and harsh conditions, a good decision support tool is needed. With such decision support tool, operators of the power grid can know the best actions to perform for different scenarios

Traditionally, decisions are made based on the results of steady state analysis and eletro-mechnical transient simulations. However, both steady state analysis and electro-mechanical transient simulation are not enough for future power grids. Future power grids have much more complicated dynamic interaction among many new components with different dynamic time constants. One example is FACTS devices, such as STATCOM and SVC. Their high bandwidth controllers could destabilize the power grid [1]. Another example is the PV inverters. The control of PV inverters can have huge impact on the system performance and stability [2]. Moreover, power grids are protected by protection relays. The coordination among different protection relays is essential for the proper operation of the grid. However, the traditional tool cannot consider the protection relay with other devices at the same time. Even they do, they cannot consider protection relays in very detail. Therefore, a new decision support tool is needed for the future operation of the power grid.

To be able to model system dynamics in great detail: from the dynamics of power electronics converter to the longer time-scale dynamics, such as governor and voltage regulator, electromagnetic transient simulation (EMTP) should be used [3]. To test actual protection relays and FACTS controllers, real-time simulation should be used. Because with real time simulation, the power grid can be simulated in real time so that protection relays and FACTS devices can interact with the simulation in the same way with the real power grid. Therefore, a real-time electromagnetic simulation should be used. However, to be able to run this kind of simulation, lots of computation power is needed. Currently on the market there are two companies producing this product: RTDS [4] and OpalRT [5].

At Dominion Energy we are fortunate to have the largest amount of RTDS computation power in the east coast of US. We use RTDS to perform numerous system studies and root-cause analysis. In this paper, we will show how to use RTDS as a real-time decision support tool for electric transmission grid operation. We will use two examples to demonstrate the usage of RTDS as real-time support tool: remedial action scheme (RAS) and black start. In Dominion Energy, RAS is implemented in several areas. By using RTDS, we create an actual replica RAS relay panel and corresponding system model for hardware-in-the-loop analysis. We not only model the system before and during arming of the RAS, we also model response and restoration after RAS is executed. RTDS is useful to provide real-time dynamic analysis and feedback to the operators.

Dominion Energy updates their system restoration plan (SRP) during blackstart regularly. For each SRP, the corresponding detailed RTDS models are built. The SRP models include not only the cranking path models but also the re-synchronization of any cranking paths to restore the transmission systems. In addition, the hardware-in-the-loop testing is performed with the actual protective relays along our black start cranking paths. Because fault current level during blackstart is much smaller than in normal system conditions, the proper coordination of protection relays is challenging. It is important to test whether the protection relays operate correctly. Moreover, RTDS user interfaces are built so that we can observe the response of different variables and determine the status of the system. This can provide a real-time feedback to system operators during black start restoration procedures.

In this paper, we will also discuss several challenges and suggested solutions in RTDS implementation. First is the limitation on the number of nodes that RTDS can simulate. How to eliminate the nodes that are outside the study zone and represent the eliminated nodes with equivalent nodes are important issues. Second is about the issue of model accuracy. With inaccurate models, the simulation results from RTDS will be inaccurate. Currently, we use the dynamic parameter data converted from PSS/E planning models. However, these dynamic parameters are not necessarily updated and some parameters may be missing. In this work, we will show the preliminary way of using available measurements from PMUs, digital fault recorders, and SCADA data to validate the dynamic parameters.

The organization of the papers is as follows. Section two will discuss RAS while section three will discuss blackstart. Section four will show the screen shot of the interface and some simulation result. Section five will present the conclusion and future works.

Remedial Action Scheme (RAS)

RAS is a particular type of system protection [6]. When power systems experience certain contingencies, the systems may operate at their limit and experience instability or blackout. To save the systems from instability or blackout, a special protection is performed. Some examples of RAS are 1) to perform intentional islanding, 2) to perform line switching, 3) to perform large scale of load shedding, etc.

In one of Dominion service territories, due to the retirement of power plant and prolonged process of permitting and building transmission lines, under certain contingencies, such as the loading level exceeds by certain percentage and certain transmission lines trip, the system will experience voltage instability. To save the system from voltage instability, RAS is performed to shed part of the loads.

There are several stages in RAS. First is the arming of RAS. When the system loading is higher than the specified level while some generators are out of service, the RAS is armed. Second stage of RAS is execution. There is a list of contingencies where RAS is executed. This particular RAS performs a set of actions, such as transmission line topology change and load shedding. The third stage is when the contingencies are removed and the system is ready to be restored back to normal. In this stage, the restoration of the loads that is shed by RAS is performed.

There are several purposes of using RTDS to model the RAS. Firstly, the dynamic simulation of each stage of RAS is performed. We would like to know the transient response when the specified contingencies occur. This allows us to see the deterioration of voltage profile of the system. We would also like to know the response when RAS is executed. This allows us to see how RAS can help the rest of the system remain stable. Lastly, we would like to see the response when the loads are being restored. This could help operator to determine whether this restoration sequence is feasible or not. In some cases, we may encounter problems such as overloading of transformer, overloading of transmission line, under voltage and over voltage issues.

To quickly restore customer loads that are tripped by RAS, having a good restoration plan is essential. However, restoration is not a trivial task. There are several practical considerations. One is the load characteristics. Depending on the duration of outage, the cold-load pickup value will be high and the load diversity factor will be low. This will result in a high loading of the system. For distribution transformer, if it is overloaded, it will take longer time for the transformer to cool down before the transformers can be energized again. This will prolong the restoration time. Therefore, it is important to make sure when the load is picked up, there is no over-loading. In addition, when motors are energized, they will draw huge magnetizing current, which in turns increases the loading of transformer. In RTDS, we model the load in great detail such that we can simulate the increased loading when the loads are energized.

With more accurate models of the system, we can determine how to restore the load. Traditionally, only steady state analysis is used. But with RTDS, the detailed dynamic simulation can be performed. The response of different restoration paths can be easily determined. Based on the response, we can decide whether the restoration path is good. In the design of restoration, there are multiple ways to restore the system. Some possible options are: 1) should we should energize this set of customers or the other set of customers, 2) should we keep feeder connected when we energize the buses, or should we disconnect all the load connected at feeders, 3) should we energize the buses of this voltage level before energizing the buses of the other voltage level, 4) should we close this transformer that is connecting different voltage level first or the other one, etc. The RTDS model can help us to determine the performance of different options and find the optimal way to restore the loads.

In addition, RTDS can be used as the real-time decision support tool. Because RTDS can simulate the system in real-time, it is possible to explore different paths for different scenarios. Sometimes unexpected events may occur, such as the available resources or available transmission line is not available anymore. In these scenarios, we need to find alternative restoration plans. With RTDS, we can determine which alternative restoration plans are safe and secure. Before executing the plan, we can use RTDS to simulate the restoration plan to make sure there is no violation. Once it is verified, the restoration plan can be executed.

Another application is to train operators. RTDS can simulate power system in real time; the response of any operation on power systems can be calculated in real time. In addition, because it is simulation, all possible scenarios can be created without causing any physical damage to equipment. Therefore, RTDS is a great tool for training operators so that they can know the proper procedure to operation the system with RAS. For expected scenarios, the operators can operate the given set of procedure designed for this particular scenario. For an unexpected scenario, the operators are trained to make the decision based on their experience.

Blackstart

Blackstart plays an important role in the reliability of utility [7]. With climate change, the chance of nature disaster is getting higher. Moreover, the power grids are operated near their limits, the change of wide-spread blackout is larger than ever. Therefore, how to restore the load from the blackout is critical for utility, especially serving the critical load, such as nuclear power plant. In Dominion Energy, the blackstart restoration plan is updated regularly. The plan is updated based on numerous factors, such as the available black-start resources, loading conditions, etc. If the restoration plan causes some violation, the restoration plan will be adjusted accordingly.

In Dominion, restoration plans are verified with EMS and PSS/E. In both cases, the black-start restoration plan is verified based on power flow model; only steady-state is considered. In the steady-state analysis, voltage magnitude and the loading of transformer and transmission line are checked such that the black start plan does not have violations. However, blackstart plan is a sequence of actions. Even though each step, such as energizing a line or a load, satisfies the steady state condition and has no violation, it is still possible that during the transition period, from steady state point A to steady state point B, the system experiences instability, such as generator losing synchronization, transient voltage too high, inrush current too high for prolonged time period, etc. Therefore, it is far from enough to use steady state analysis. In Dominion Energy, RTDS is used to perform electromagnetic transient simulation to study the transient response of blackstart paths.

In addition, protection coordination is another issue. During blackstart, because of relatively small fault current resources, the fault current is usually smaller than the fault current during normal conditions. It is more challenging to perform protection coordination and distinguish normal loading from fault current. Making sure the protection is secure and reliable is vital for the proper operation of power grid. In Dominion Energy, hardware in the loop simulation (HIL) shown in Figure 1 is performed to test and validate the protection setting and coordination in great detail.

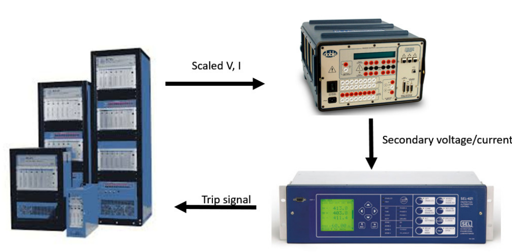


Figure 1: Hardware-in-the-loop simulation setup

In HIL, the power system is modeled in RTDS while the protection relay with the field setting is used to perform protection logic. There are three interfaces. First, RTDS sends the voltage and current measurement to Doble power amplifier via analog output card (GTAO). Secondly, the Doble power amplifier sends the secondary voltage and current to the relay. Thirdly, the relay sends the breaker control signal to the breakers modeled in RTDS via digital input card (GTDI). Since the range of GTAO output is 10 V while the Doble power amplifier voltage output range ix 300V while current output range is 30A, the scaling factors for voltage and current in the GTAO card should be set correctly.

Because of the limited amount of power amplifiers, the number of relays simultaneously tested in HIL is limited. To test multiple relays and check the coordination for more complicated scenarios, we model several relays in RTDS by using the relay model provided. We convert the protection relay setting files into the setting of the relay model in RTDS. In this way, there is no input/output interface and the hardware requirement is greatly reduced. We can test multiple protection relays without limits in a more economical way.

During blackstart, unexpected things may happen. For example, a particular line is unable to be energized, or a blackstart unit is not available. There are so many N-2 contingencies; it is almost impossible to find the alternative path for each N-2 contingency beforehand. Therefore, it is important to have the capability to determine the alternative path in real-time. In Dominion, we set up the RTDS lab in such the way that it is running in parallel with system control center (SOC). There is a multiple communication link, including audio and video, between the RTDS lab and control center.

RTDS can provide two applications in real time support. First application is to find alternative actions based on the current status of the system and the simulation results. Alternative actions can be found via trial and error or via some sort of optimization methods. Second application is to see the response of the next action that SOC is going to executed. If the response is satisfactory, the control center can execute the next actions. The actions can be one step or multiple steps. Because Dominion has powerful RTDS capability, these two applications can be performed in two instances at the same time. One instance find the alternative routes that satisfy the restoration criteria while the other instance is to simulate the actions that SOC is going to execute.

Challenges and Proposed Solution

There are several challenges in building the RTDS model for RAS and blackstart studies. In this section, we will describe these challenges and the methods we use or plan to use to overcome these challenges. The first challenges is about eequivalent circuit and network decomposition.Even though Dominion Energy has relative large amount of RTDS computation power that can relative large size of network, it is impossible to simulate the whole Dominion network. Therefore, we need to reduce the network that is far away from our study area with equivalent circuit.

There are several step of performing network reduction for a given event under study. The first step is to optimally choose the buses to be retained. To identify those buses, the event is simulated with the full model (eastern interconnect system) and the buses whose angles and voltages change considerably are selected. For generator buses, since the voltages are stiff, the reactive power outputs of these generators are monitored. These buses along with the region where the event is being studied make up the internal buses while the rest of the buses are external buses. We do not model the dynamics of buses that do not react to the event. The second step is to reduce the external buses. For load buses that are in the list of external buses, we reduce them by using the static equivalence function provided by PSS\E. For generator buses that are in the list of external buses, they are converted into negative loads. The third step is to deal with the boundary buses. The boundary buses are the internal buses that are connected to external buses. We use infinite classical generators to represent the inertia of rest of the grid. The internal impedance is tuned for these equivalent generators to limit the Q support we can get from these units.

Notice that network reduction is based on the assumption that the external area buses do not react to the event under study. This reduced model is only applicable when we study the given event or events which have a smaller impact on the external buses than the given event. In RAS, we have two network models: one is before RAS is executed while the other is after RAS is executed. The former one is used to investigate the impact of contingencies and the need to execute RAS; the latter one is used to investigate the restoration strategies after RAS is executed.

Another issue that is unique to RTDS is how to decompose the network into different subnetworks. RTDS takes advantage of parallel computing; it solves different subnetworks using different processors in parallel. Long distance transmission lines are used to decompose the network. It is relative easy for the network whose subnetworks are interconnected via long transmission line. However, it can be quite challenging to break the network whose subnetworks are interconnected via short transmission line. In RAS modeling, we encounter this issue. During the network reduction, short lines that interconnect boundary buses are created, causing the boundary buses to be in the same subnetwork. Since the boundary buses are connected to the most part of the network, the whole network is in the same subnetwork, making the network decomposition quite challenging. To solve this problem, trade-off is made. The number of boundary buses is reduced such that the network can be divided into several sub-networks at the expense of simulation accuracy.

The second challenge is related to generator models. RTDS simulates the dynamics of the networks, including electro-magnetic and electro-mechanical phenomena. One of the key components is generator models. Generator models include the parameters of a generator itself, exciter and governor. Since these parameters have significant impact on the simulation results, it is important to have accurate generator models to have correct simulation results.

The generator models are imported from PSS/E planning model. The accuracy of these models is acceptable. However, to make sure the model is correct, we double check with the generation branch of Dominion Energy. Moreover, we use the testing results during generator commissioning. We perform the same testing procedure as generator commissioning in RTDS. By comparing the testing result, we can fine tune the generator parameters.

However, it may be long time ago since the generators were commissioned. The generator model may change over time. We are in the processing of using big data technique to fine tune the parameters. In the territory of Dominion Energy, there are numerous PMU and DFR installed across the grid. Some of them are installed at the buses that are at or near the generators. We use playback functionality in RTDS; we represent the rest of the network with an equivalent source, whose voltage and angle are playback from PMU or DFR data. Note that the data corresponds to different disturbances, such as faults in the system. To fine tune the generator parameters, we apply the same disturbance and compare the real and reactive power at the location of PMU and DFR. Once the real and reactive power from the RTDS is the same as that from PMU and DFR, the generator models are found. This is only one of the methods we are trying. We are exploring other methods that help to identify the generator models.

The third challenge is related to automation and User Interface. To facilitate RAS and blackstart studies, we automate some steps in the studies. We utilize “Script” function offered by RTDS. The scripts can perform numerous functions that do not require human interaction. For example, we can catch and save the simulation results at each step of restoration during the blackstart and after RAS is executed. We can also automatically bring the system back into the initial status, such as the status before RAS is execute, or the status before the blackstart plan is executed. No manually changing the status of the breaker is required. Moreover, protection validation can be performed automatically as well. We apply the fault at different locations in the system and catch the simulation results automatically. Based on the simulation results, we can determine whether the protection relay functions as expected. To further facilitate the protection validation, we are in the process of building the Python code to perform the protection validation, such as the timing of Zone 1 and Zone 2 protection coordination.

One of the key functions of RTDS simulation is to show the simulation result to the users. Therefore, the interface is vital to show the key information. On the RTDS interface, the voltage, power flow can be shown on the one-line diagram. Moreover, the indicators that show whether the bus has over-voltage, under-voltage, whether the frequency is too high or too low, whether the line is overload, are placed on the interface. Because the system is relatively big, the one-line diagram and user interface, such as plot and control, will be not shown in the same window clearly. Moreover, RTDS cannot display the interface in different windows.

Therefore, we put important indicators together such as voltage profile and frequency in the same group. This group can be moved around at the same time when the switching order is performed. In this way, while the users are performing the switching at different locations, the window can be dragged to the location near the switch so that the response of the system due to the switching can be viewed easily.

Case Studies

Here we show two simple examples. The first is the RAS shown in Figure 2 shows one of the RAS in Dominion Energy. This is the interface of RTDS. The users can open/close the breaker and adjust the loading, either individual or overall. The monitoring interface and plot function are grouped together so that they can be moved around as the switching of the load and transmission lines are performed.

Figure 3 shows one of the blackstart paths in Dominion Energy. The users can open/close the transmission line and the loads. The dynamic response voltage at each bus can be observed. Figure 4 shows the example of HIL protection studies. One actual SEL-421 with field setting is interface with RTDS while the other relay is modelled in the RTDS with field setting. The fault is applied at the location which is Zone 1 for the RTDS relay and Zone 2 for actual SEL 421. The response of the relay signals shows that the RTDS relay instantaneously trip with Zone 1 while SEL-421 time-delay trips with Zone 2. This shows that the protection coordination between these two relays are correct.

Conclusions

In this paper, we described how Dominion Energy uses RTDS as a real-time decision support tool. We used RAS and blackstart as two examples. We also described some challenges and the corresponding solutions. In the future, we will continue to use RTDS as a real-time decision support tool in other application in Dominion Energy. At the same time, to have more accurate simulation results, we will improve the accuracy of dynamic model by using big data analytics with PMU and digital fault recorder data.

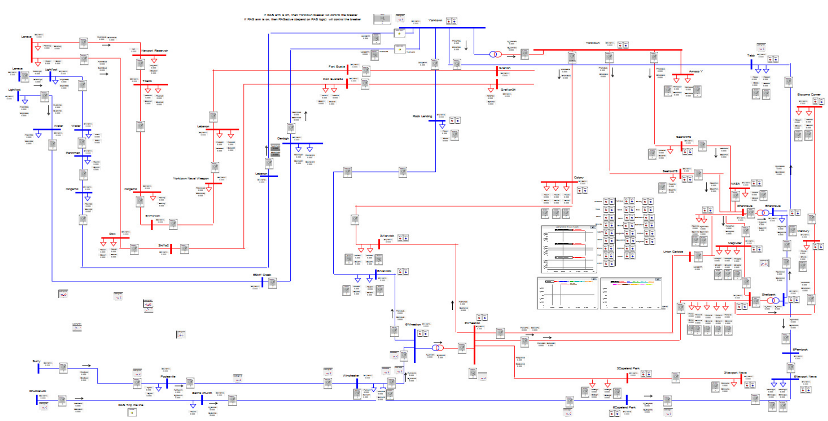


Figure 2: Example of RAS

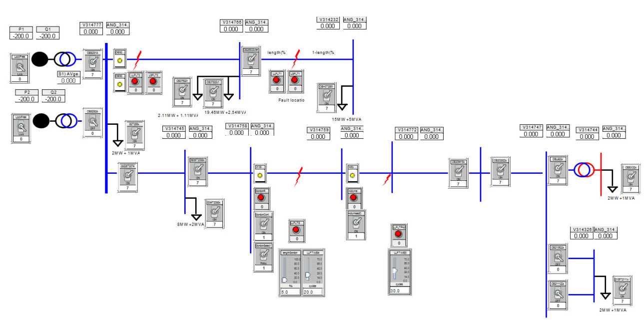
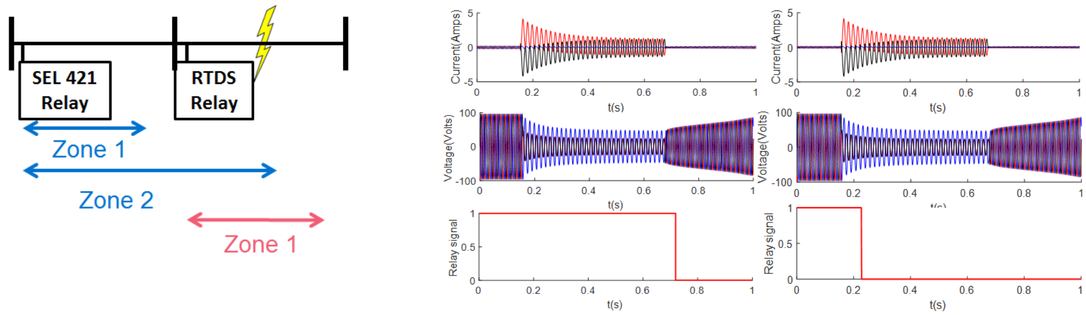


Figure 3: Example of one blackstart path



(a) (b)

Figure 4: Protection coordination testing

BIBLIOGRAPHY

[1] Harnefors, L., Wang, X., Yepes, A. G., & Blaabjerg, F. (2016). Passivity-based stability assessment of grid-connected VSCs—An overview. IEEE Journal of emerging and selected topics in Power Electronics, 4(1), 116-125.

[2] Wen, B., Boroyevich, D., Burgos, R., Mattavelli, P., & Shen, Z. (2016). Analysis of DQ small-signal impedance of grid-tied inverters. IEEE Transactions on Power Electronics, 31(1), 675-687.

[3] Dommel, H. W. (1986). Electromagnetic Transients Program: Reference Manual:(EMTP theory book). Bonneville Power Administration.

[4] RTDS, https://www.rtds.com/

[5] OpalRT, http://www.opal-rt.com/

[6] Bertsch, J., Carnal, C., Karlson, D., McDaniel, J., & Vu, K. (2005). Wide-area protection and power system utilization. Proceedings of the IEEE, 93(5), 997-1003.

[7] M.M. Adibi L.H. Fink "Power System Restoration Planning", IEEE/PES Winter Meeting, 1993.