

An Interactive, Stand-Alone and Multi-User Power System Simulator for the PMU Time Frame

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Abstract— This paper discusses the simulation of electric power systems on the phasor measurement unit (PMU) time frame in which the power system dynamics are solved with time steps on the order of an electrical cycle. The paper presents an environment in which flexible and extensible communication and interactive control action capabilities are included, including support for the C37.118.2 and DNP3 protocols. The paper describes the environment design, and includes examples of how it is being used both for stand-alone simulation and as part of a multi-user simulation environment.

Keywords— power grid simulation, PMUs, c37.118, DN3, visualization, interactive control

I. INTRODUCTION

Interactive electric power system simulations have a long history, with a nice summary of their impact discussed in [1]. An important distinction between the different approaches is the simulation time frame for their associated dynamics. The first packages, known as operator training simulators (OTSS) or dispatcher training simulators (DTSs), began appearing around 1980 [2]. With an OTS the power system was modeled with a uniform, but not constant system frequency approach. This allowed for consideration of dynamics on the order of one second, allowing for interactive simulations to train electric grid operators. In [3] a constant frequency model was used to allow for longer term simulations on larger systems. A primary use of such packages was to explain the operation of the electric grid to students and nontechnical professionals in the electric power industry.

A shorter time scale, interactive simulation environment was presented in [4] that allowed for simulating electric grids with a step size on the order of $\frac{1}{4}$ or $\frac{1}{2}$ cycles. This is known as transient stability time frame, but since it roughly corresponds to the sampling frequency of PMUs, an alternative name is the PMU time frame. Hence the dynamics of the generator machines, exciters, governors and stabilizers can be represented, along with dynamic models for the load. During the simulation each bus has its own frequency, yet the transmission network equations are still represented as algebraic constraints.

The contribution of this paper is to build on and extend the results from [4]. In particular, the paper provides a description of this interactive PMU time frame dynamics simulation environment (abbreviated as DS), focusing on the design of

the environment, its visualization capabilities and some example applications. The DS includes two simulation modes. The first allows for simulating electric grids in the PMU timeframe. The second mode allows for simulations using a uniform frequency model, similar to the approach of [2]. In this mode integration occurs with a time step sizes of tenths of seconds to seconds, with the generators treated similarly to how they are treated in the power flow. That is, as a source of real power with either a fixed voltage magnitude or a fixed reactive power contribution.

The DS can be run either in a stand-alone mode, in which a single user is interacting with the simulation, or in a server mode in which a variety of clients are communicating with it using potentially a variety of different protocols. One use of the DS is to provide a flexible platform that can be used to simulate the different layers such as the communication layer, and application testing layer, of smart grid hardware that might compose a next generation energy management system (EMS).

The paper has the following additional sections. Section II discusses the design of the power system simulation itself. Section III describes its capabilities for stand-alone simulation and visualization, while Section IV discusses its use in multi-user simulations. A free educational version of the package is available for download at [5].

II. A PMU TIMEFRAME INTERACTIVE SIMULATION

The DS is a time-domain, positive sequence power system simulation package that can simulate dynamics on the PMU time frame. It can be configured to run either in real-time, slower than real-time or faster than real-time up to computational limitations. A PC can solve systems with several thousand buses and detailed machine dynamics in real-time, and can simulate the small systems, such as the 42 bus system presented here, at more than 100 times real-time. And it can either run a simulation for a fixed time duration, or for an open ended amount of time.

In contrast to packages such as [3], the DS is not designed to create the associated power system case. Rather, it loads the information needed for the simulation using the PowerWorld Simulator pwb and tsb formats [6]. The input can be divided into two main categories.

First, there is the model of the power system itself, including all the associated dynamics models for the devices and their protection systems. This input is often identical to what would be included in a transient stability study, though it could be augmented with longer timeframe models. Because of its support for the pwb file format, existing transient stability cases can usually be directly loaded.

Second, there are models for how the power system will change over time. These models can be divided into two subcategories. First, there are discrete events, such as the opening of a transmission line at a specific time, or the opening or closing of a generator. Usually these are predefined to specify a particular scenario. Second, there are continuous events, such as the variation in the bus level load. Because of the DS's support for the tsb format, load variation can be specified at essentially any time resolution (e.g., hourly or minute-by-minute) for almost any reasonable duration (e.g., for an hour or a week) (a discussion of the creation of realistic load var [7]). Changes in generator availability are specified using the same time resolution as the load, and are usually set by limited the maximum MW value for the generator.

Because the DS is an interactive environment, during the simulation the model can be also be changed by user created events. These can occur either from a single user when the DS is used in the stand-alone mode, or from multiple users when used in its server mode. All changes can be stored for later playback of the simulation, and the DS can optionally store time domain results throughout the simulation.

In the DS the transient stability simulation is solved using the simulation engine from [8]. This provides access to a large number of different models of power system components, such as electric machines, exciters, governors, stabilizers, relays, load models, and many others. In also allows for the import and export of models in industry standard formats, and allows for the efficient solution of large power system cases. In addition to transient stability level dynamics, this engine also includes the option to simulate using a uniform frequency model when less detail is needed to simulate larger systems.

In the DS the simulation engine runs in a separate thread. This allows it to function relatively independently. Model generated events, such as tripping a device due to a modeled protection system action, are handled internally within the simulation. At a user specified, integer number of time steps, the simulation engine transfers simulation data to the main DS environment. This information is then available for display, or when running as a server, for communication to the clients. At a potentially faster rate user commands are passed back to the simulation engine.

III. STAND-ALONE MODE AND VISUALIZATION FEATURES

As first presented in [4], a key aspect of the DS is its focus on interactive power system visualization. This is illustrated by way of the Figure 1 example, which shows the online diagram for a fictitious 42 bus system. During the simulation all the analog fields are updated as data is received from the simulation engine, and animated flow arrows are used to show the flow of real and/or reactive power in the system [9] (in

Figure 1 green arrows are superimposed on the transmission lines and transformers to visualize the flow of the real power). In addition, the per unit bus voltage magnitudes can be visualized using a color contour [10]. In Figure 1 this is done using a blue-red color mapping. During a simulation the on-line contour can be updated in a separate thread at a user selected rate of up to perhaps 10 Hz (depending on contour resolution and machine speed), allowing for good visualization of power system voltage effects.

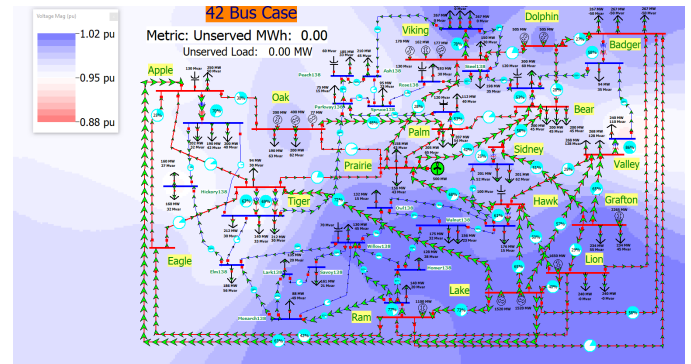


Figure 1: 42 Bus Case System Online with Voltage Contour

One common application of the DS is to run relatively short-term (e.g., several minutes), real-time simulations of potentially extreme power system disturbances. An example, first presented in [4], is shown in Figure 2. Here the starting point is the Figure 1 case, and then over the course of 80 seconds the impact of a tornado moving by an electrical substation in simulated. In Figure 2 strip-charts are used to show one minute of data, with the top chart showing the system frequency and the bottom one showing several of the bus voltage magnitudes. The strip-charts can be predefined and stored in the input case file, allowing for a wide range of customization. Given the oscillations on the system, apparent in the Figure 2 strip-charts, this scenario was designed to have important dynamics within the PMU time frame. Tabular displays are also available to show many additional details about the system model, with Figure 3 showing an example of some of the bus fields.

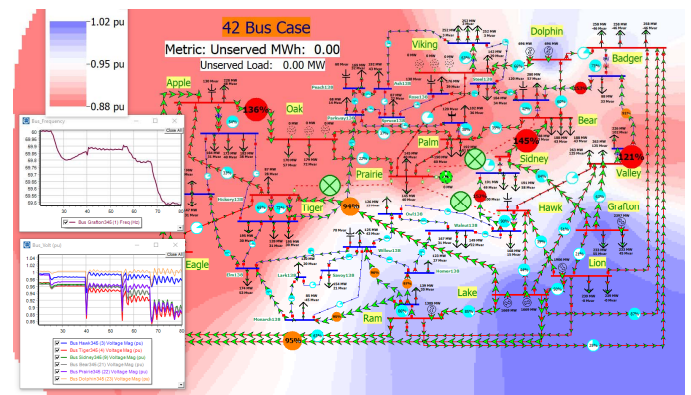


Figure 2: 42 Bus Case During an Extreme System Disturbance

Number	Name	Nominal KV	Bus Energized?	Voltage Mag (pu)	Voltage Angle (deg)	Freq (Hz)	Gen MW	Gen Mvar	Load MW
3	Hawk345	345	Closed	0.990	32.910	59.877	0.00	0.00	0.00
4	Tiger345	345	Closed	0.943	19.106	59.877	0.00	0.00	91.92
5	Hawkeye138	138	Closed	0.925	9.204	59.877	0.00	0.00	314.17
6	Elm138	138	Closed	0.942	12.871	59.877	0.00	0.00	182.73
7	Badger345	345	Closed	0.995	7.829	59.876	0.00	0.00	793.99
8	Apple345	345	Closed	0.938	18.199	59.877	0.00	0.00	245.86
9	Sidney345	345	Closed	0.954	15.730	59.876	0.00	0.00	0.00
10	Valley345	345	Closed	0.973	32.729	59.877	0.00	0.00	533.26
11	Apple138	138	Closed	0.938	10.184	59.877	0.00	0.00	591.17
12	Sidney138	138	Closed	0.983	15.150	59.877	0.00	0.00	396.67
13	Walnut138	138	Closed	1.004	14.474	59.877	0.00	0.00	326.93
14	Hawk138	138	Closed	0.985	15.261	59.877	0.00	0.00	173.86
15	Eagle345	345	Closed	0.953	21.455	59.877	0.00	0.00	0.00
16	Tiger138	138	Closed	0.927	9.818	59.877	0.00	0.00	552.51
17	Owl138	138	Closed	0.992	14.993	59.877	0.00	0.00	130.26
18	Oak345	345	Closed	0.977	15.299	59.876	706.38	613.32	387.37
19	Viking345	345	Closed	0.986	10.833	59.876	535.82	324.62	149.13
20	Palm345	345	Closed	0.951	11.227	59.876	0.00	0.00	407.89
21	Bear345	345	Closed	0.954	11.631	59.876	0.00	0.00	594.13
22	Prairie345	345	Closed	0.959	13.554	59.876	0.00	0.00	309.10
23	Dolphin345	345	Closed	1.001	13.344	59.875	1000.49	337.21	0.00
24	Valley138	138	Closed	0.914	16.118	59.877	0.00	0.00	253.96
25	Badger138	138	Closed	0.968	5.104	59.876	0.00	0.00	92.69
26	Viking138	138	Closed	1.017	4.725	59.876	0.00	0.00	795.56
27	Apple138	138	Closed	0.944	-8.291	59.876	0.00	0.00	206.79
28	Peach138	138	Closed	0.946	-8.021	59.876	0.00	0.00	182.15
29	Palm138	138	Closed	0.956	-3.593	59.876	0.00	0.00	110.30
30	Bear138	138	Closed	0.964	1.180	59.876	0.00	0.00	256.01
31	Spruce138	138	Closed	0.945	-8.455	59.876	0.00	0.00	93.55
32	Parkway138	138	Closed	0.949	-4.564	59.876	0.00	0.00	73.81
33	Steel138	138	Closed	0.963	0.062	59.876	0.00	0.00	195.44

Figure 3: Tabular Display of Bus Values

A complimentary application of the DS is to provide a much longer term simulation of more normal system operation. This addresses an important gap in many university level power system educational programs in which students previously did not have a chance to gain substantial experience in operating at least a simulated power systems. To provide such experience DS scenarios could be designed to show how the electric grid changes over the course of perhaps many hours. Using the previously mentioned tsb files time-varying load profiles can be defined a priori at any desired time resolution (e.g., piecewise linear, five minute load variation). The seemingly more random small variations in the power system load can be simulated in the transient stability engine using load models that include a small noise component.

An example of such a scenario is shown in Figure 4. Here the simulation is run over the course of an hour, during which the load is increasing. In the figure the strip-charts are configured to show ten minutes of data, with the top strip-chart showing the frequency at several buses, the middle one showing the total real power generation and load, and the bottom one showing several bus voltage magnitudes. In this scenario the student is tasked with doing generation and voltage control.

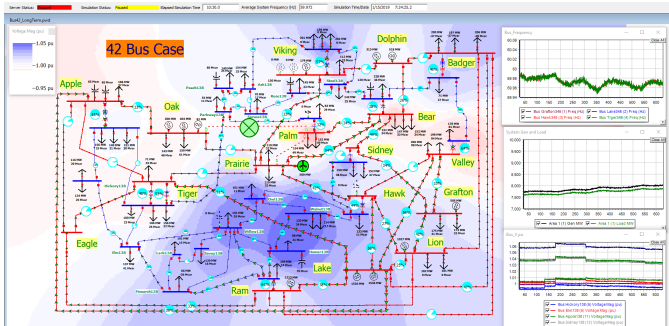


Figure 4: Longer Term, More Normal Operation

A design decision in creating such scenarios is the associated simulation speed. Real-time simulations have the

advantage of accurately conveying power system dynamics and providing a feel for how quickly decisions need to be made during actual operation. Of course the disadvantage is longer term simulations can take a long time. An alternative, at least for small systems, is to run the simulations faster than real-time. As an example, the Figure 4 scenario is set to run at six times real-time. The degree of automation included in the scenario, such as the use of automatic generation control, can be customized.

In the DS there are several different optional ways to do interactive control, depending on the degree of realism desired. The simplest, quickest, and perhaps most unrealistic, is to allow unconfirmed control directly from the onlines. Examples could include opening or closing transmission lines, loads or switched shunts. This could be most useful in an education or engineering setting in which the focus is on the dynamic behavior of the system, rather than trying to duplicate the behavior of a SCADA system in which such commands would usually require some type of confirmation. An option is available to either require confirmation when control is done directly from the online or to prevent all direct online control.

More detailed control can be done from specific device dialogs. As an example, Figure 5 shows the dialog for a generator, in which commands can be issued to change various generator values. When running in the PMU timeframe the DS will usually include detailed models for the generator's exciter and governor. Therefore the commands are setup to change the input to these models, such as changing the exciter's voltage setpoint or the governor's real power setpoint, as opposed to changing the generator terminal values such as would be done in a power flow simulation. Commands are also available to either open the generator, or (optionally) close (i.e., reconnect) the generator. When closing a synchronous generator the assumption is that the generator is already spinning at the system frequency. However, an option is available to close with an initial voltage angle difference, providing a simple approximation for a synchro-check relay.

Generator Information

Bus Number: 3, Bus Name: Oak345, ID: 3, Nominal Voltage: 345.0

Area: 1, Zone: 1, Substation: 2, Generator MVA Base: 250.00

Field Values: Elapsed Time: 0:13.7, Bus Voltage Information: Voltage (p.u.): 0.9846, Voltage (kV): 339.7, Angle (deg): 17.193, Freq (Hz): 60.004

Power Limits: Min MW Limit: 0.00, Max MW Limit: 200.00

Power Information: Total MW: 200.196, MW Setpoint: 200.000, Total Mvar: 112.986

Controls: Generator Status: Open, Control Time (Seconds): 0.00, New Voltage Setpoint (pu): 0.983

Change Voltage Setpoint, Change Real Power (MW) Setpoint, Open Device, Close Device

Close Initial Angle Difference (Deg.): 0.000, Confirm All Control Changes (Global Option): checked

Figure 5: Generator Dialog

During the simulation all events can be logged, with the option to store the results in a pwb format file. This allows later playback in other programs, such as the PowerWorld transient stability. Figure 6 shows an example of the DS event log. The last column in the figure, “Level,” shows the source of the event. Example sources include 1) “Predefined,” which is used for events that are setup before the simulation starts (in Figure 2 example this included the opening of the devices due to the simulated tornado, 2) “Relay Trip,” which indicates the event is due to the action of a simulated relay as part of the protection system, and 3) “DS User,” which indicates the control actions the user has taken during the simulation. A key aspect of scenarios could be if the user does not take corrective actions quick enough, some of the generation is tripped due to the action of their over excitation relays.

Time (Seconds)	Model Type	Object	Description	Level
1	10.0000 AC Line	Bear345 (21) TO Prairie345 (22) CKT 1	Apply Solid Fault (3PB)	Predefined
2	10.0500 AC Line	Bear345 (21) TO Prairie345 (22) CKT 1	Open	Predefined
3	25.0000 Gen	Prairie345 (22) #1	Open	Predefined
4	40.0000 AC Line	Hawk345 (3) TO Prairie345 (22) CKT 1	Apply Solid Fault (3PB)	Predefined
5	40.0500 AC Line	Hawk345 (3) TO Prairie345 (22) CKT 1	Open	Predefined
6	55.0000 AC Line	Tiger345 (4) TO Prairie345 (22) CKT 1	Apply Solid Fault (3PB)	Predefined
7	55.0500 AC Line	Tiger345 (4) TO Prairie345 (22) CKT 1	Open	Predefined
8	56.6417 Gen	Oak345 (18) #3	Gen Overexcitation Relay OEL1 action: Open (TripMW=200)	Relay Trip
9	56.6417 Gen	Oak345 (18) #2	Gen Overexcitation Relay OEL1 action: Open (TripMW=77.11)	Relay Trip
10	60.1667 Load	Oak345 (18) #2	Open (TripMW=190)	DS User
11	64.0000 Load	Oak345 (18) #1	Open (TripMW=200)	DS User
12	66.6458 Gen	Oak345 (18) #1	Gen Overexcitation Relay OEL1 action: Open (TripMW=400)	Relay Trip
13	68.5858 Gen	Bear345 (21) #1	Open (TripMW=200)	DS User
14	71.2500 Load	Bear345 (21) #2	Open (TripMW=200)	DS User
15	74.1667 Load	Bear345 (21) #3	Open (TripMW=200)	DS User
16	76.6625 Gen	Viking345 (19) #3	Gen Overexcitation Relay OEL1 action: Open (TripMW=177)	Relay Trip

Figure 6: DS Event Log

The interactive, variable simulation speed of the DS allows for a wide variety of different applications. For example, Figure 7 shows how the previous 42 bus system could be configured for use in an educational setting to demonstrate load dynamics. Here, rather than running in real-time or faster than real-time, the DS is run at 1/20 real-time, with interactive control used to demonstrate the opening and closing of a load modeled to include a percentage of induction machine models. The use of both a color voltage magnitude contour and several strip-charts helps to show the system-wide impacts of starting the induction machines. In the figure the larger strip-chart on the right shows the load’s real and reactive power (using red and green curves respectively), with the opening of the load indicated by the values going to zero, and then it being closed 0.7 seconds later. Because of the much slower than real-time simulation, the dynamics, including the start-up transients, can be demonstrated. Note that the load’s real and reactive values change as it is restarted due to the dynamics of the induction machines. During the simulation the voltage magnitude contour is dynamically updated to show the impact on the system voltages.

An example of the DS being utilized on a 2000 bus case for university undergraduate education is described in [11] Figure 8 shows the DS display for this system. Because a synthetic electric grid was used, developed using the approaches presented in [12] and [13], the associated power flow and dynamic parameters are publicly available at [14]. Included with these cases are geographic coordinates for all the electric substations. The 2000 bus “Texas” case used here is geographically located in the US state of Texas. In this

scenario, which is configured to run in real-time with full dynamics and a simple transmission protection system, several transmission lines were assumed to be sequentially opened because of storms. Over the next minute or so the students then needed to take corrective control actions, such as redispatching generation or shedding load, to prevent a voltage collapse

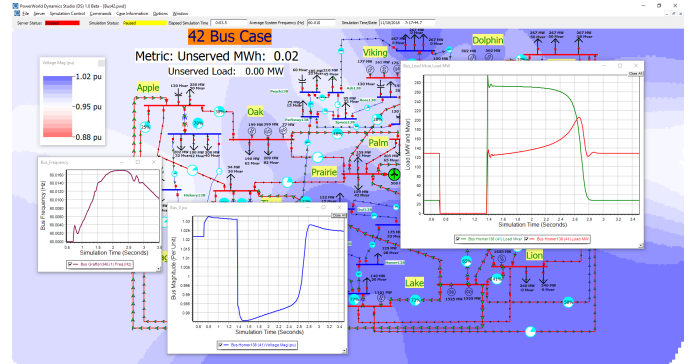


Figure 7: Load Opening and Closing Dynamics

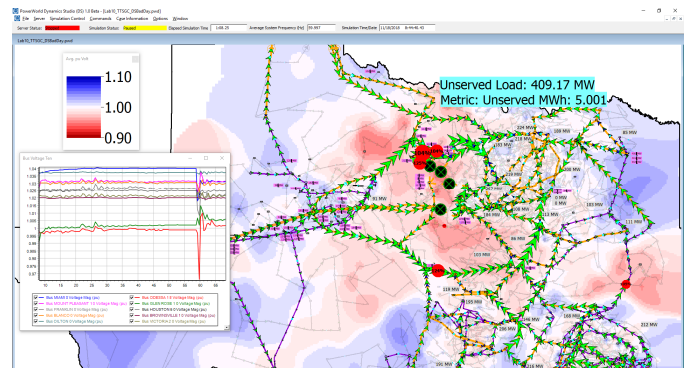


Figure 8: Simulation with a 2000 Bus Synthetic System

IV. MULTI-USER SERVER MODE

In addition to running with a single user in its stand-alone mode, the DS also implements a server, allowing connection with various clients. Currently the DS supports three different protocols: 1) its own DS protocol, 2) the IEEE C37.118-2 synchrophasor communication protocol [15], and 3) DNP3 [16]. All three protocols can be used by the DS to send data to the clients, while the DS and DNP3 protocols can be used by the clients to send commands back to the DS, potentially modifying the simulation. In addition, the DS protocol, which is publicly available in the free DS education version download [5], allows for the DS to send a dictionary to the clients, describing the associated power system model including the geographic coordinates of the electric substations. This server capability greatly extends the usage of the DS, so that users are able to write scripts to validate the proposed control strategy, or use the DS as a simulation engine to build other applications, such as a multi-user simulation.

As an example, the remainder of this section presents a web-based system developed by some of the authors that

allows multiple users to operate the same simulation simultaneously and has an interface to show the real-time data, statistics and notifications. This system utilizes web clients that communicate with the DS through a broker, which acts as a bridge to transfer information from the DS to the clients and vice versa. Figure 9 shows the overview display of the web client, in which the client can query the DS to obtain sufficient geographic information to build a oneline diagram. Then, during the simulation the client can obtain a wide variety of different values about the real-time status of the simulation, including the overall status of the grid in the current area, the total cost of the generation, the status of the generation capacity and the branches that are about to reach their limits.

As shown in Figure 9, analogs and graphics are used to show the status of the system including transmission line or transformer (i.e., branches) overloads. Once the violating branch appears, the user or users can locate the branch and adjust the generator power output to eliminate the violation. As an example, Figure 10 shows a branch overload (on the “VICTORIA 3-TAFT 1” branch); an associated dialog then provides more detailed information about the branch. By clicking on other branches and substations on the map, users may explore more details about the elements. In particular, substation dialogs have multiple tabs that let users examine the buses, loads and generators inside the substations.

This multi-user simulation was built to give users more insights about the operation of the grid and the needed coordination between different operators. With this goal, a scenario was created using the previously mentioned 2000 Texas case with load variation. In this scenario, three users are operating the grid of southern Texas, with three goals: 1) keeping the area control error (ACE) as close to zero as possible; 2) keeping all devices within their limits with branch MVA flow and bus voltage magnitude limits enforced, and 3) dynamically adjusting generator outputs according to the marginal cost to decrease the total cost. For the scenario considered here the total wall clock simulation is set for 10 minutes, with the simulation running at a fixed scaling of 60 times faster than real time.

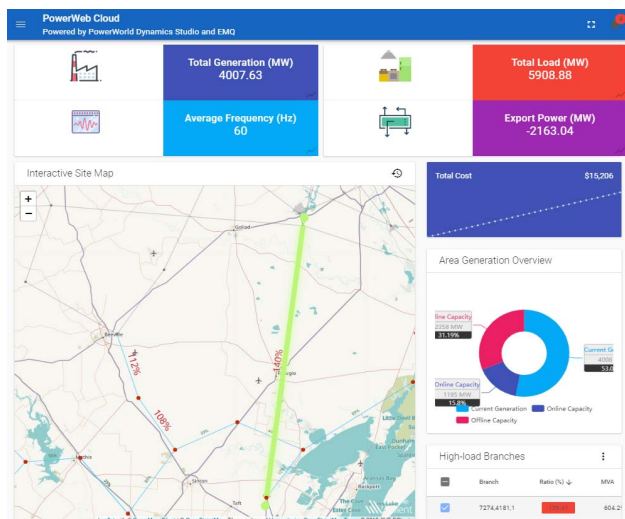


Figure 9: Example DS Client Simulation Interface

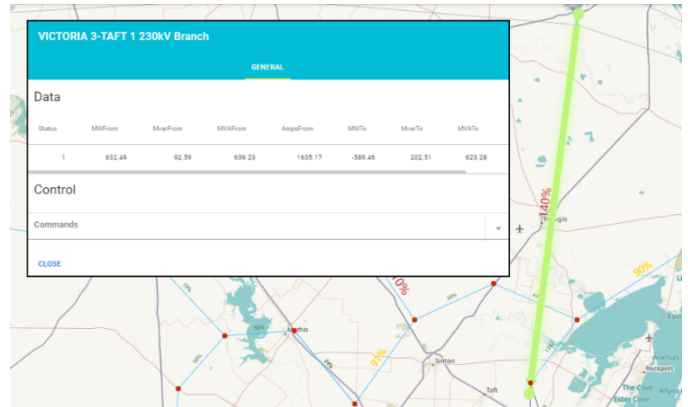


Figure 10: DS Client Branch Location and Generator Dialog

Before the simulation the users are assigned a role in which they either 1) controlling the generation, 2) doing reactive power control, or 3) functioning as a reliability coordinator with overall grid oversight. An example of the generator operator user interface is shown in Figure 11. The interface allows the user to adjust the power output, change the voltage magnitude setpoint, open/close the generators and enable/disable the automatic generation control. All communication between the client and the DS is done using the DS protocol. When the simulation is started, initially the users area facing a large ACE value due to the shortage of online generators, so they need to close other generators and adjust the power output. Then, many zones will begin to have low voltage due to the lack of online reactive power support which requires users to switch in some of the shunt capacitors that are close to zones of concern. The case itself will run into a blackout if no action or inappropriate actions are taken during the simulation. Eventually, after the simulation, users are able to get a report which has the measurement data, the total cost, the actions taken and the violations that occurred during the simulation and use it for further research.

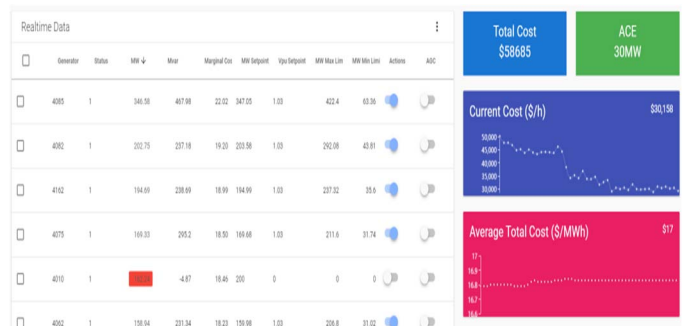


Figure 11: DS Client Generator Operator Interface

V. SUMMARY AND FUTURE DIRECTIONS

In summary this paper has presented an interactive, PMU-time frame, power system simulation and visualization environment. The use of an existing power system transient stability simulation engine allows compatibility with a wide variety of existing power system models and cases. It can be

used in either a stand-alone mode, or as a server to allow for extensible multi-user simulations.

There are many promising directions for future work with a few provided here. First, the DS itself could be modified to include additional algorithms and visualization techniques to increase situational awareness. Second, there is a need to develop a wide variety of cases and scenarios that can be used with the DS for power system education. Third, the communication capabilities of the DS could be utilized for the development of a wide variety of federated simulation environments including the incorporation of more power system hardware.

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