An On-line Electric Power Distribution System Simulator

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***Abstract*—The modern power system is currently undergoing a rapid transformation from centralized generation to decentralized and distributed generation. The distributed generation is connected at the distribution level and may consist of a large number of small generators with stochastic power output. Therefore, planning and operation of the future distribution grid requires new tools to ensure reliable and economical operation. One such tool is an on-line simulator. A system that uses an on-line simulator in the Energy Control Center (ECC) will enhance the operators' situational awareness as well as operational decision making. This paper proposes a framework for an on-line, close to real time simulator, connected to a graphical user interface emulating the Energy Control Center. The framework can be used for both planning and operation of the distribution grid. It can also be extended as an interface to other infrastructure simulators.**

***Index Terms*—Co-Simulation, Load Flow, Power Distribution System, Power System Simulation, Real Time Digital Simulator.**

I. INTRODUCTION

The increased penetration of Photo-Voltaics (PV), coupled with advances in grid tied inverter technology and fast control elements, has created complex dynamics in the traditionally passive distribution grids [1]. Unlike the traditional distribution grid, which does not require real time monitoring. This modern grid requires sophisticated monitoring capabilities to ensure reliable, economical, and safe operation. Additionally, the operators need to understand the complex dynamics of the system [2] so that optimum, timely operational decisions can be executed to control the system [3].

In distribution grids with significant penetration of PV, the state of the art planning process uses quasi static time series analysis (QSTS) [4]. This study captures the daily and seasonal variability of loads as well as the distributed generators. By doing so, a QSTS study provides an accurate understanding of the temporal dynamics of the system state. For example, understanding the temporal variation of the voltage regulator and distribution static var compensator (D-SVC) taps, as well as grid support provided by the PV, over a long time range are important for both planning and operational purposes. QSTS gives an insight into how the distribution network should be optimized, since the output of the study can be used to implement optimum congestion management as well as economic optimization. However, due to both the data and computation limitations, it is not possible to analyze the system for each and every possible contingency. This leaves a void in the decision support tool set of the Energy Control Center (ECC).

This void can be filled by operating an on-line simulator fused with the real system. By using this simulator, the ECC operators can get a clear idea of how different controller actions will influence the system state. The controller actions refer to manual operation of slow control devices such as tap changers and SVCs, fast control devices such as dispatchable micro generation and battery banks, as well as control of circuit breakers (the control of circuit breakers will result in reconfiguration of the network topology). This will also help the system operator create optimum contingency plans and be prepared with optimal control action schemes to operate the system in an emergency situation. This simulator will be operating close to (near) real time. The deviation from real time is due to the time required to conduct QSTS computation, data analysis, information transfer, and synchronization. This simulator can be converted to a real time system by adding a forecasting engine.

This tool will enable the operator to determine the consequences of their decisions by simulating the actions before actual execution. Optimum decision will be taken by the operator based on indices such as voltage deviation, number of tap change operations, and total system losses. Additionally, it will provide the operator the ability to observe portions of the system, which are otherwise unobservable. On-line simulation, however, requires synchronization of system state between the simulator and the real system. For example, a trip of a certain circuit breaker needs to be mirrored on the simulator by feeding the captured real time signals into the simulator. The model for the network, changes in the system state of the real model, the load profiles, and real time or archived weather data are inputs to the simulator. The current state of the art for

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this technology is the distribution system state estimator [5], where the objective is to find a good estimate for the system state. The state estimation technology looks from past to the present but unfortunately does not help the operator look to the future.

Previous work shows that it is possible to use OpenDSS as a distribution network simulator to conduct real time hardware in the loop type of simulations in a Labview platform [6], [7]. The uniqueness of our work is that we are looking at real time modeling from a system perspective, and not from an equipment perspective. Therefore, this framework useful for the system operators as a support tool. It is expected to be used in a co-simulation environment similar to [8] but in a close to real time mode.

This paper outlines a framework for an on-line electric power distribution system simulator. The remaining sections of the paper describe the simulator that was implemented based on the aforementioned conceptual framework and provide examples for typical usage.

II. Distribution System Simulator

The conceptual framework of the on-line electric power distribution system simulator is given in Fig. 1. This framework integrates hardware measurements, forecasts as well as contingency studies to the ECC operator. This framework is described below.

The real electrical system sends its status changes such as circuit breaker switching or trip as well as measurements from devices such as micropmus to a data aggregation and synchronization platform. This platform formats the data and synchronizes the signals with different latencies and update speed to a format that can be fed into the model integration platform.

The model in integration platform integrates data from the field with other data sources and sends it to the power system computation engine. Examples for other data sources are weather station data, other interconnected infrastructure data, and control actions implemented by the HMI.

The computation engine, which is an online model running on the OpenDSS platform, will then compute the system state and send the results back to the model integration platform. The results will then be formatted and sent to the HMI for visualization and from the HMI to the rest of DMS ECC to be used for other purposes such as archiving and post analysis. The data aggregation and synchronization platform also feeds the field data directly into the DMS to ensure that states with direct measurements are available to the operators with minimum delay. The operator, in the human block, in Fig. 1 will then have a broad view of past and current system status to make optimum decisions. The operator also has the possibility to use the QSTS computation engine to simulate the system for a future time horizon, starting from a current system state, to understand the temporal impacts of their decisions before implementing them.

In the case study used to implement the simulator, which is based on the modified IEEE 34 bus feeder [9], Matlab GUI is used as the Operator SCADA and mirrors the real system HMI. This SCADA additionally shows system characteristics such as total feeder loss and total mean squared error for voltage. The simulator uses the OpenDSS engine for QSTS. The simulation engine is driven via the Common Object Model (COM) interface using Matlab in step mode. At each step, data is exchanged, control actions executed, and sub-systems synchronized, as shown in Fig. 1.

TABLE I
SPECIFICATIONS OF THE PV SYSTEMS

Connected Bus	kVA	$P_{mpp}(kW)$	Voltage Level (kV)
844	1000	900	24.9
890	750	500	4.16
860	1250	1000	24.9
828	200	150	24.9
806	100	100	24.9
836	150	150	24.9
840	250	200	24.9
812	250	225	24.9

The step size used in the simulation is one second. The OpenDSS computation engine can complete a power flow for the 8500-node test feeder, which is a good representation of moderately large real distribution feeder, in less than one second. This is the reason a step of one second is used for this simulator. However, based on the system architecture and user requirements, this can be adjusted. For example, if the parallel processing version of the OpenDSS computation engine is used with a multi-core processor supported system, the maximum step size enforced due to the delay in the power flow computation engine can be significantly reduced.

A modified IEEE 34 bus test feeder was used as the sample power system. The modified IEEE 34 bus test feeder includes the PV plants given in Table I. Additionally, the feeder voltage was changed from 1.05 pu to 1 pu to adjust the system optimally for reverse power flow based operation. The placement and sizing of the PV plants, given in Table I, are based on load allocation of the IEEE 34 bus test case, given in Table II.

In order to simulate the external data fed into the simulator, a set of 12 hour solar irradiance measurements from a dataset in [10] given in Fig. 2, was used for the case study.

A. Implementation

The current version of the simulator has the features listed below:

- Control of Q-injection in two PV plants in manual mode
- Ability to arbitrarily switch volt-var controllers on and off
- Display power injection of the PV power plants and main feeder
- Ability to control the main feeder and section circuit breakers

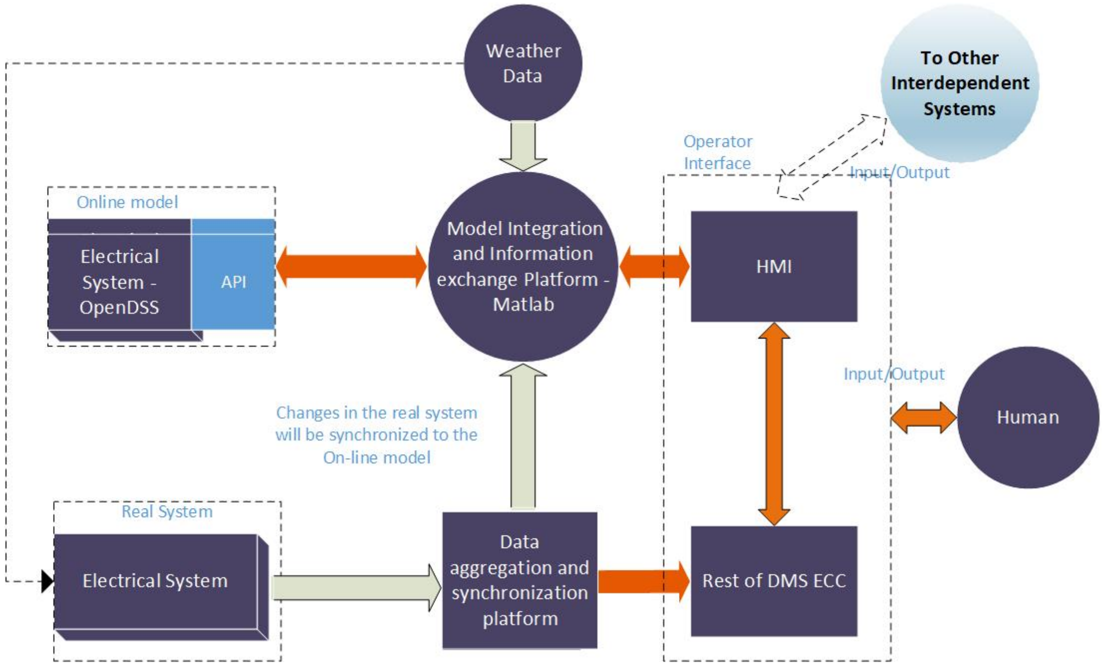

Fig. 1. Conceptual framework of the on-line electric power distribution system simulator

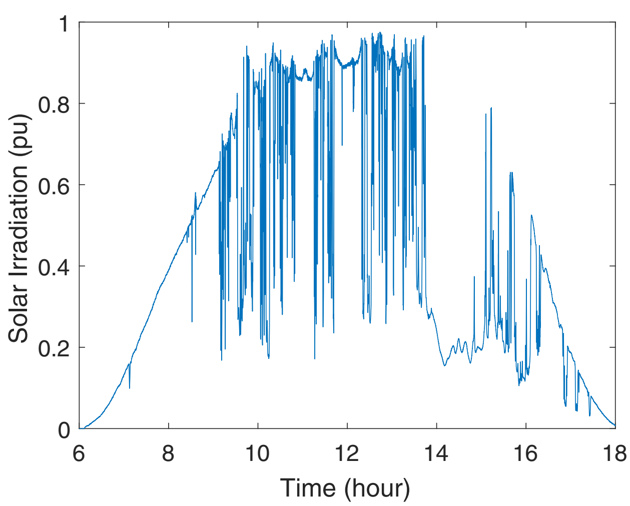

Fig. 2. Input solar irradiance profile [10]

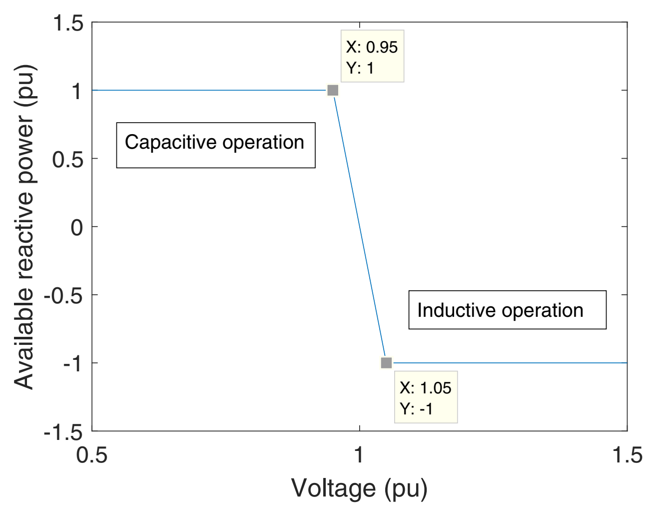

Fig. 3. Implemented volt-var controller [11]

- Show dynamically the line which has the highest losses
- Display system mean squared voltage error
- Display total system losses
- Display numerical values of the voltages at the critical nodes

The simulator can be used to conduct long term planning studies as well as short term and close to real time operational studies. These studies are discussed in the next section.

B. Planning Studies

For planning studies, the simulator is accelerated by increasing the step size. The inputs are previous measurements taken in a similar previous operational state of the system. This study will help the power system planner understand the temporal dynamics of the system, resulting in better system design. This is an important study especially when there is significant DER penetration.

1) Inferences from the simulator output when solar irradiance is minimal: At the start of the simulation, it is still dark, volt-var control (Fig. 3) is on, and the value of solar irradiance is zero as shown in Fig. 4.

The feeder state is examined starting from the substation feeder-head (node 800). The total system losses shown on the upper left hand side of the GUI is 314 kW at an instance

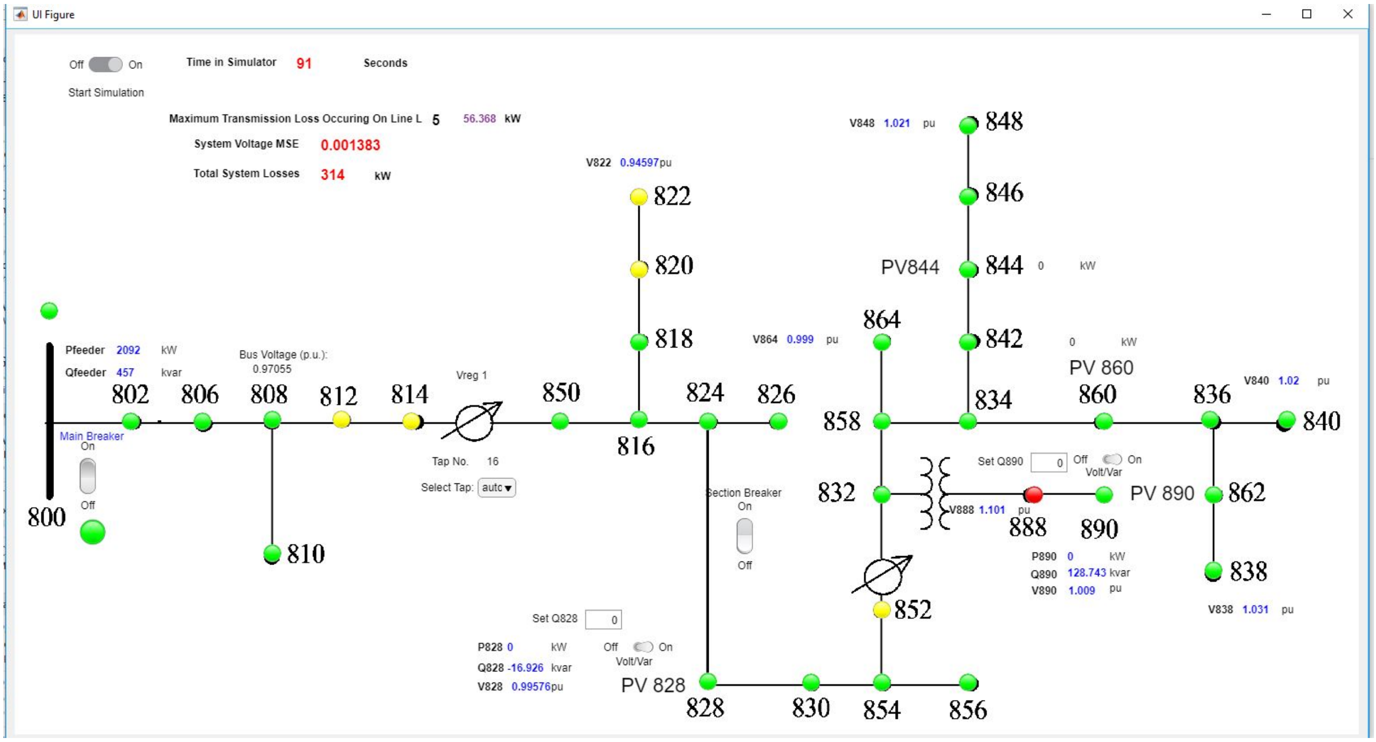

Fig. 4. Simulator output at night time with volt-var control

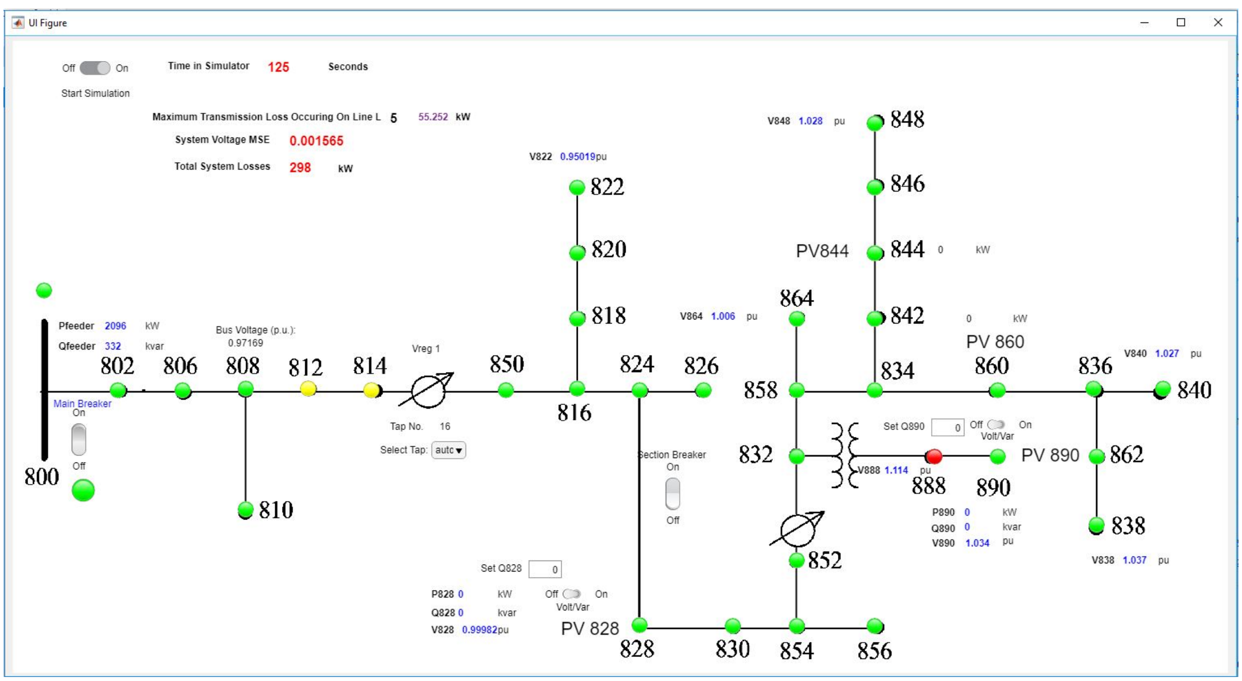

Fig. 5. Simulator output at night time without volt-var control

when the feeder is exporting 2092 kW of power, meaning that the distribution system power losses amount to 15%, which significantly exceeds the allowed losses for economic operation. Additionally, a sixth of the total losses occur in Line 5. This points to the fact that re-conductering or adding a new line will help to decrease the losses occurring in the feeder.

The nodes 812 and 814 show under-voltage. This can be solved by decreasing the impedance of Line 5 which has the highest losses (L5 connects nodes 808 and 812). The regulator at this point is at its highest tap position, 16. This shows that the regulator can not operate in a flexible manner when DER is not supplying power to the system. The planner needs to either increase regulating capability or add an extra switched capacitor to increase the controllability of the system, especially since this operating state persists for almost of half the day.

It is also observed that nodes 822 and 820 are at under-voltage. These laterals require some voltage support or strengthening of the conductors to ensure that voltage is within the limits. The next low voltage occurs at node 852, which connects the primary of the second voltage regulator. This again points to the fact that this connection requires enhancement. The critical design flaw in this system is, however, at node 888. When the volt-var control is in effect, it is observed that node 890 is at a satisfactory 1.009 pu, whereas the voltage at bus 888 is at a very high 1.101 pu. This points to a high impedance of the line that connects nodes 888 to 890 or high currents flowing in this line. This critical issue needs to be rectified. This design flaw shows that even if volt-var control is enabled, it is not possible to comply with voltage standards under the current system design.

The additional inferences are that the total losses of the system are excessive. Further changes to the system are required to address this undesirable performance of the system. Ideally, the system needs to be optimized from a planning perspective, even before looking at methods to optimize from a control & operation perspective. The simulator shows that the substation feeds in 194 kVar to support voltage of this system.

The 1 pu setting of the main transformer voltage is an important inference from this study. When it is uni-directional power flow, it will always be a voltage drop from the feeder-head downstream. Therefore, setting the voltage at feeder-head to a higher value will help with the voltage regulation. However, with bi-directional power flow this will cause high voltage when the DER pushes active power to the main grid. This infers that when there is a possibility of reverse power flow, the optimum feeder voltage profile can only be obtained by setting the (static) substation feeder voltage at a default value of 1 pu to counter the effects of reverse power flow.

Another inference is that the system state is based on its historical performance, meaning that the system has some memory effects. This points to another advantage of conducting QSTS with visual support, which is that memory effects are taken into account, unlike in static studies.

As the next step in this study, volt-var control is disabled and system performance is observed through the simulator. The result given in Fig. 5 shows that system performance does not deteriorate when volt-var control is disabled for this operating condition.

2) Inferences from the simulator output when solar irradiance is at its peak: The system performance close to the peak solar irradiance levels is shown in Figs. 6 and 7. At this operating point, the distribution system is experiencing a reverse power flow of almost 1 MW.

It can be observed that system voltage, especially at nodes 852, 888, and 890, are enhanced when volt-var is activated, even though system losses increase from 96 to 172 kW.

The example analysis shows how this simulator can be used to support distribution system design and the planning process. It will help the designers to understand the system requirements as well as be useful as a guideline for congestion planning and hosting capacity studies.

C. *Operational Studies*

In this section the application of the simulator in the ECC for operation and training purposed are discussed.

1) Optimal system operation: The economic objective in design and operation of a distribution system is profit maximization. This means that loss should be minimized in all operating conditions. A special point of operation, where there is minimum energy exchange between the feeder and the main grid, is shown in Fig. 8. The loss value at this operational point is 81 kW, which is only a third of the losses when the system is operated without DER, and the MSE is at a minimum, giving the ideal voltage profile. As shown in Fig. 6 and 7, the loss increases when the reverse power flow increases. The conclusion is that, for the simulated system, the losses can only be reduced by minimizing the net power exchange between the feeder and the main grid. It should also be noted that the voltage quality of the system in this operation scenario is the best by far when compared with all the cases studied using the simulator. This shows that the system voltage can be optimized while minimizing losses by connecting battery storage. The scenario makes an economic case due to the savings resulting from loss minimization. The simulation also shows that there are voltage problems at bus 888 and 890, which need to be addressed either by using voltage regulation services of the connected PV or by other methods.

2) Manual Regulator operation: The next study shows how tap changer operation causes system voltages to change. It is an ideal example to show how the simulator can be used either as an operator training tool or as a testing platform to support real time decision making. Before conducting any of these operations, the operator can simulate the impact of the actions on the simulator to understand whether it will enhance or degrade system performance.

Fig. 9 shows the system state when volt-var is disabled and tap changer 1 is set to manual mode, -16 tap. The red indicators show that downstream voltage drops significantly. Not surprisingly, the voltage of 888 and 890 drops to a lower level and is now within the system voltage limits. This special scenario comes to play because the irradiance level in this simulation is negligible. Significant over-voltage will be observed when there is generation from PV plant at bus 890. This scenario and many others, such as how arbitrary Q injection from PV and disconnection of different parts of the system affects system dynamics, and how new

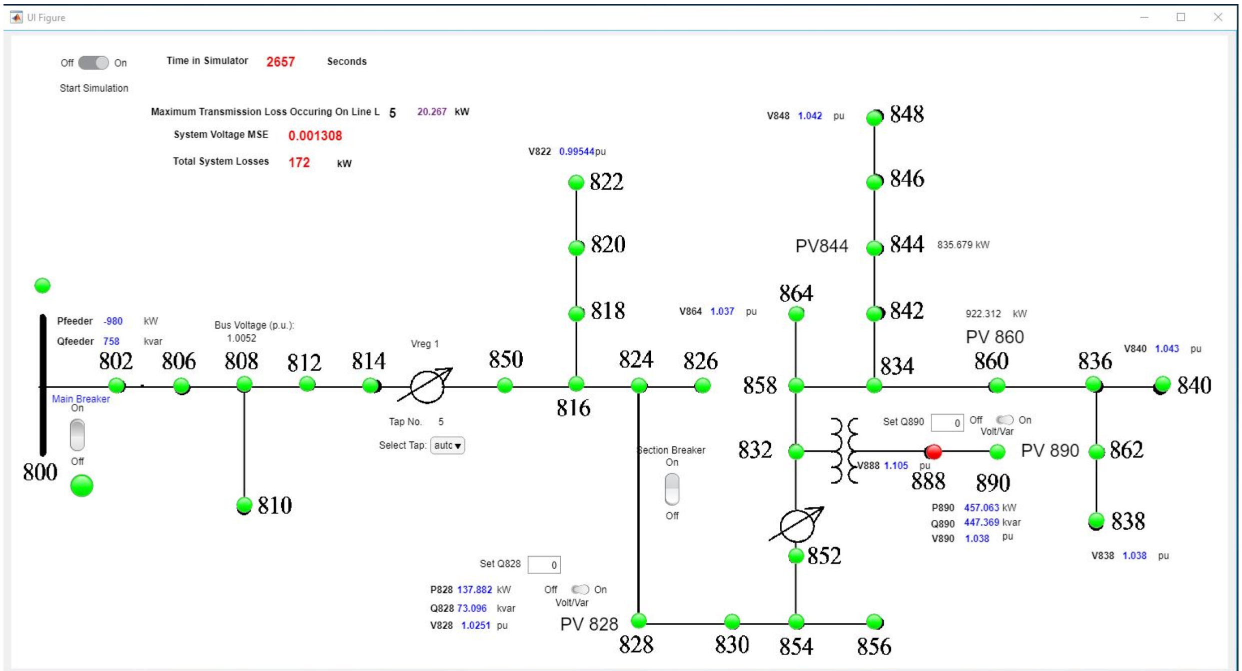

Fig. 6. Peak reverse power flow with volt-var support

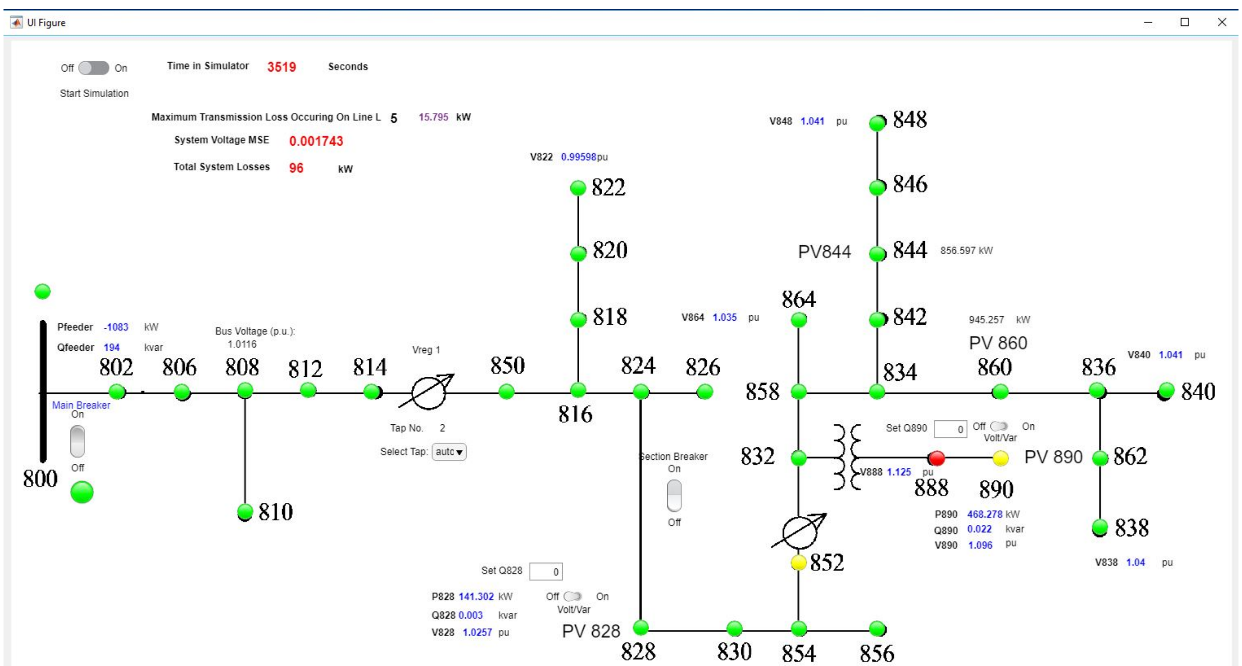

Fig. 7. Peak reverse power flow without volt-var support

control strategies will affect the system performance, can be understood by using this simulator.

D. Challenges

The challenge of using the Matlab app designer platform for HMI development is that it is severely limited in terms of GUI development facilities. For example, even the facility to embed an image into the simulator is yet to be implemented by Matlab for the app designer framework. As a result, this study had to use indirect, imprecise techniques to place the image.

In addition, the COM interface of Matlab applies late bindings which significantly decreases the performance. Due to these deficiencies, future development of this simulator will be ported to a different development platform. A preliminary

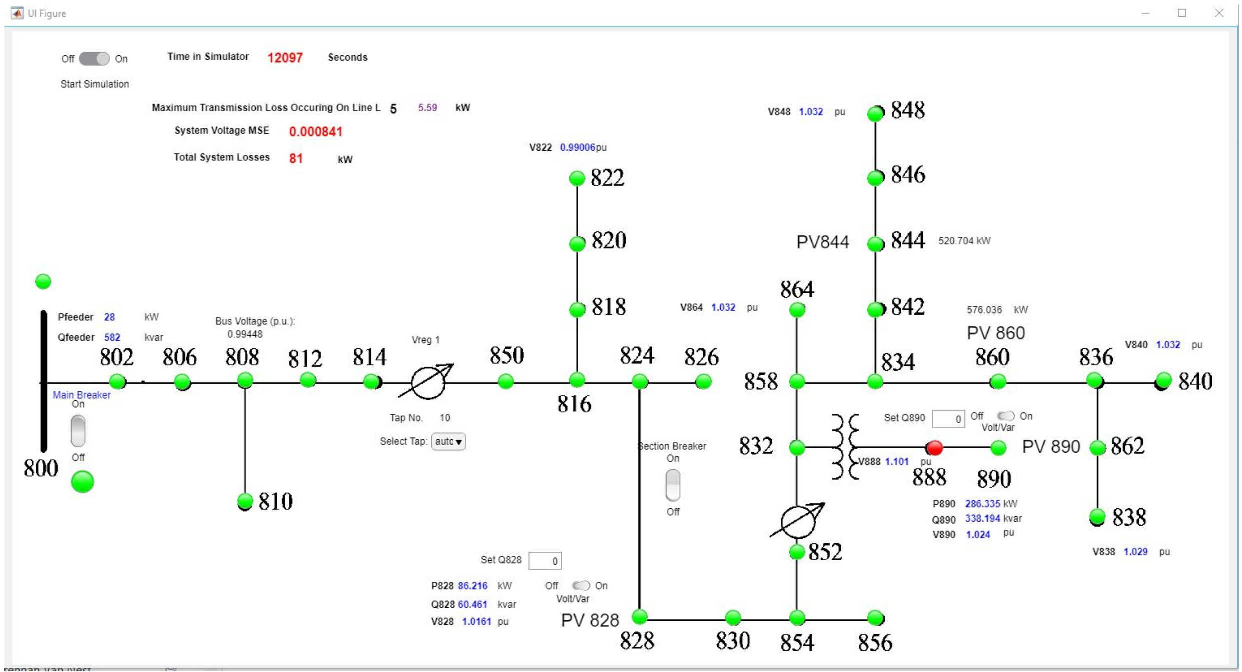

Fig. 8. Minimized energy export (28 kW) - optimal economic operation

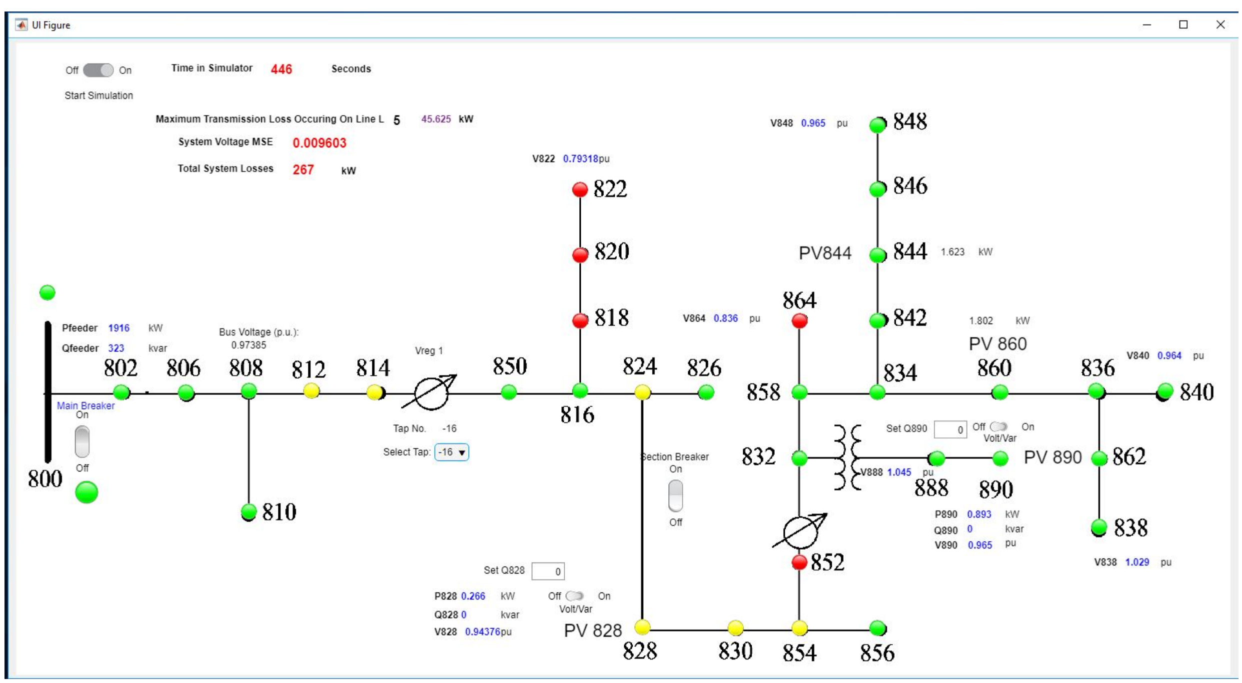

Fig. 9. Without voltvar at tap -16

literature review shows that the Python platform combined with QT libraries [12] will be a much better platform to extend this system.

III. Conclusion

This paper proposes a framework for a real time simulator for distribution systems that can be used for operational and planning purposes. It can also be used for operator training with real time system inputs. Apart from Matlab, the other components of the system are open source, and therefore this is a possible alternative to a more expensive hardware-based real time simulator. The simulator will only capture dynamics with a time constant of one second or longer. Since the input variables to the model vary at a lower frequency, this will provide the accuracy required for modeling a distribution grid.

The example studies described in this paper show some facets of how the simulator can be used as a training tool as well as a decision making tool at the ECC.

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TABLE II
IEEE 34 BUS LOADS

Bus	Type	A (kVA)	B (kVA)	C (kVA)
802	Y-PQ	0	15+7.5j	12.5+7j
806	Y-PQ	0	15+7.5j	12.5+7j
808	Y-I	0	8+4j	0
810	Y-I	0	8+4j	0
818	Y-Z	17+8.5j	0	0
820	Y-Z	17+8.5j	0	0
820	Y-PQ	67.5+35j	0	0
822	Y-PQ	67.5+35j	0	0
816	D-I	0	2.5+j	0
824	D-I	0	2.5+j	0
824	Y-I	0	20+10j	0
826	Y-I	0	20+10j	0
824	Y-PQ	0	0	2+j
828	Y-PQ	3.5+1.5j	0	2+j
830	Y-PQ	3.5+1.5j	0	0
830	D-Z	10+5j	10+5j	25+10j
854	Y-PQ	0	2+j	0
856	Y-PQ	0	2+j	0
832	D-Z	3.5+1.5j	1+0.5j	3+1.5j
858	D-Z	3.5+1.5j	1+0.5j	3+1.5j
858	Y-PQ	1+0.5j	0	0
864	Y-PQ	1+0.5j	0	0
858	D-PQ	2+j	7.5+4j	6.5+3.5j
834	D-PQ	2+j	7.5+4j	6.5+3.5j
834	D-Z	8+4j	10+5j	55+27.5j
860	D-Z	8+4j	10+5j	55+27.5j
860	D-PQ	15+7.5j	5+3j	21+11j
836	D-PQ	15+7.5j	5+3j	21+11j
860	Y-PQ	20+16j	20+16j	20+16j
836	D-I	9+4.5j	11+5.5j	0+0j
840	D-I	9+4.5j	11+5.5j	0+0j
840	Y-I	9+7j	9+7j	9+7j
862	Y-PQ	0	14+7j	0
838	Y-PQ	0	14+7j	0
842	Y-PQ	4.5+2.5j	0	0
844	Y-PQ	4.5+2.5j	12.5+6j	10+5.5j
846	Y-PQ	0	24+11.5j	10+5.5j
844	Y-Z	135+105j	135+105j	135+105j
848	Y-PQ	0	11.5+5.5j	0
848	D-PQ	20+16j	20+16j	20+16j
890	D-I	150+75j	150+75j	150+75j