A Distribution System Test Feeder for DER Integration Studies

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***Abstract*—The modern power system is undergoing a rapid transformation from centralized generation to distributed generation. The distributed generation consists of a large number of small distributed energy resource (DER) based generators with stochastic power output connected at different geographic locations throughout the feeder. Therefore, the operation of the future distribution grid requires novel control strategies to ensure reliable and optimum operation. This paper presents a modified IEEE 34 bus feeder test case with over 100% DER penetration. The test case includes eight PV plants with volt-var control, two switched capacitor banks, two regulators and a battery bank. The distribution feeder test case allows for benchmarking the performance of different feeder control strategies and to conduct other DER integration studies.**

***Index Terms*—DER integration, Power Distribution System, Power System Simulation, Quasi-static time-series analysis, Voltage Control.**

I. Introduction

The increased penetration of Photovoltaics (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 did not require a significant control effort, this new grid requires sophisticated monitoring and control capabilities to ensure reliable, economical and safe operation. Additionally, the operators need to understand the complex dynamics of the system [2] [3] to operate it optimally.

In distribution grids with significant penetration of PV, the state of the art planning process uses quasi-static time series analysis (QSTS) [4] [5]. QSTS provides insight into the operational characteristics of the system over a given period of time, taking into consideration all key time-varying independent variables such as DER generation, load dynamics, and topology.

Therefore, it is important to conduct a QSTS analysis when novel control schemes are proposed. The base IEEE test feeders only specify the parameters required to conduct a power flow analysis. In order to move to a QSTS analysis from a power flow analysis, additional parameters related to controllers are required. Even for a simple system, there are a large number of possible permutations and combinations for the controllers and their parameters. Therefore, a standard test feeder with set controllers and specified parameters based on a simple but realistic distribution feeder incorporating all major components will help the researcher to fast-track the research goals and to benchmark their control strategies. This test feeder is not meant to analyze dynamics related to grid forming operation of DER and is limited to grid following operation. Many test cases for grid forming operation exist in literature [6]. When a feeder is operated in grid forming mode (micro-grid) it is critical to analyze the system looking at faster phenomenon since the power electronic controls will define the performance of the system.

Reference [7] gives a case to use IEEE 34 test system as the base for grid integration studies, even though it does not include any DER. Reference [8] is a test case that is based on the IEEE 34 test feeder. However, the DER included in this study is a single 1MW PV plant. In order to provide better representation, it is imperative that the installed DER exceed 100% of the feeder capacity, while the DER consist of many smaller PV plants distributed across the feeder. Neither of these requirements is satisfied by [8].

The other work available in literature with similar scope is [9]. This test feeder is based on IEEE 37 bus test case and models the loads and PV generation from rooftop installations at a high granularity. This test case requires a significant amount of data to model and therefore is not an easy feeder to use as an initial testing platform. Note that after the control methods are benchmarked in the test feeder proposed in this study, it is important to test them again in a more detailed system such as the IEEE 8500 node test case as explained in [10], before actual implementation. This test feeder can be used as a support tool for rapid prototyping to support present and future research activities. Apart from voltage control, it can be used to cover most of the studies required for DER integration detailed in [4].

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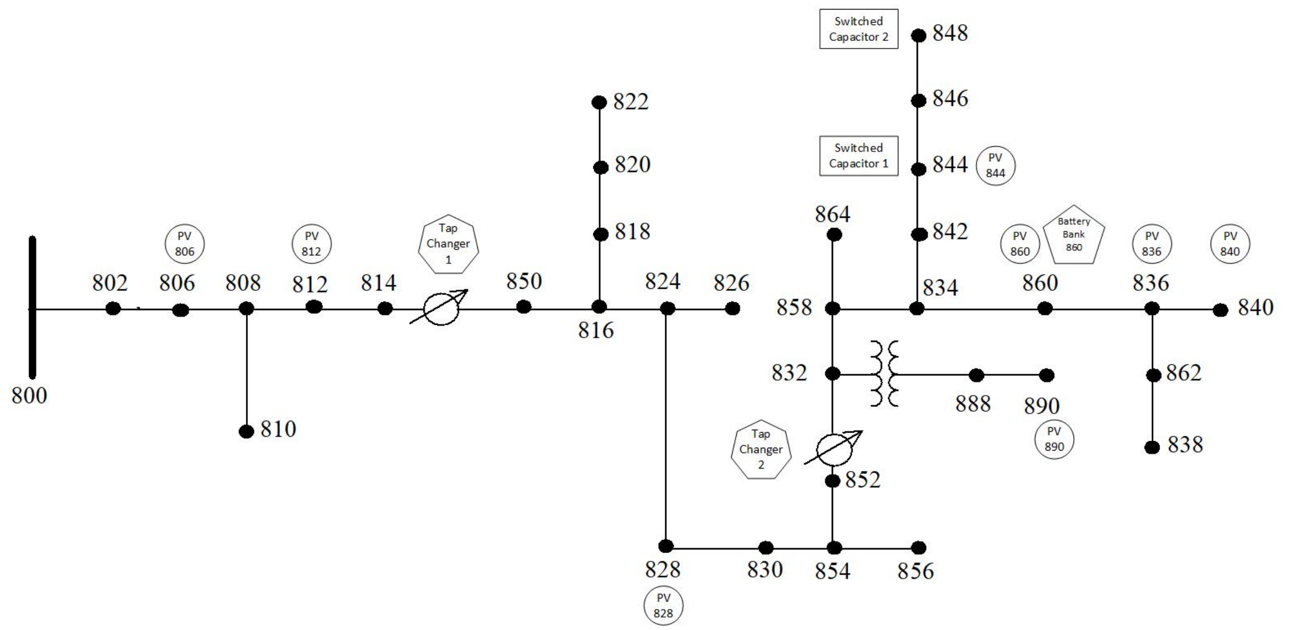

Figure 1: Single line diagram of the proposed modified IEEE 34 bus test feeder

II. Distribution System

As documented in [10], the different IEEE distribution test feeders represent different types of distribution systems. The proposed test feeder is based on the IEEE 34 test case [11] [12], which was a popular choice for DER integration studies in the past [13] [8]. It was modeled after a real distribution system that existed in Arizona in 1991 [11]. This test case is a well accepted, mature and clearly documented system [12] [14]. It is an unbalanced, long, radial distribution system. In consequence, this feeder is well positioned to create demanding requirements in the field of voltage control.

The DER of this test feeder are grid-connected PV and support components are switched capacitors, voltage regulators, and battery banks, which are the typical components of an advanced distribution grid. The components and their parameters were based on a mix of personal judgment, literature survey and on trial and error where required. The advantage of this test feeder is that any researcher can directly use this test feeder without investing the extra effort to size and place the system components and also be able to compare the performance of their algorithms with the performance of the algorithms of others in a level playing field. A unique feature of this test feeder is that it has significant reverse power flow and a DER penetration close to 150% of the feeder rating.

This test case cannot analyze DER operation in grid forming mode since QSTS can not simulate any fast, transient phenomena, which are very important when analyzing the performance of the power electronic interfaces. In this case, it is always assumed that controls are stable and settled going from one time step to another in QSTS simulations. Since the smallest time step is usually 1 second, this is a reasonable assumption. For example, it is not possible to disconnect the test case into 2 or 3 isolated units and conduct studies on it looking from a pure micro-grid operational perspective. However, this test case is ideal to be used for voltage control, congestion management, hosting capacity, component placement, component sizing and transactive energy market studies.

A. *Modified IEEE 34 test feeder*

The single line diagram (SLD) of the test feeder is shown in Fig. 1. All typical components, including transformers, loads and transmission lines stay unchanged from the original IEEE 34 bus test case [11] [12] [15]. The placement and sizing of the PV plants are based on load allocation of the IEEE 34 bus test case. The basis for this load allocation is to represent a system stressed due to deep PV penetration. The substation transformer voltage was changed to 1 pu from the original 1.05 pu, to ensure that high voltage is not experienced when the feeder is experiencing reverse power flow.

The original static capacitors are changed in the test feeder to switched capacitors to ensure better voltage control. The control parameters for the capacitors are given in Table I. The capacitors turn on when monitored voltage is $< C_{on}$. When the voltage increases over $> C_{off}$ the capacitors will turn off. C_{dt} is the dead time, the minimum time needed for the capacitor to change state from off-state back to on-state. C_{dl} is the time delay for controls operations. If the state changes before the time given by C_{dl} elapses, the control actions are reset.

$$C_{state} = \begin{cases} on & \text{if } V_{node} < C_{on} \\ off & \text{if } V_{node} > C_{off} \end{cases} \tag{1}$$

TABLE I: Parameters of the switched capacitor controller

C_{on}(pu)	C_{off}(pu)	C_{dt}(s)	C_{dl}(s)
0.95	1.05	300	15

TABLE II: 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

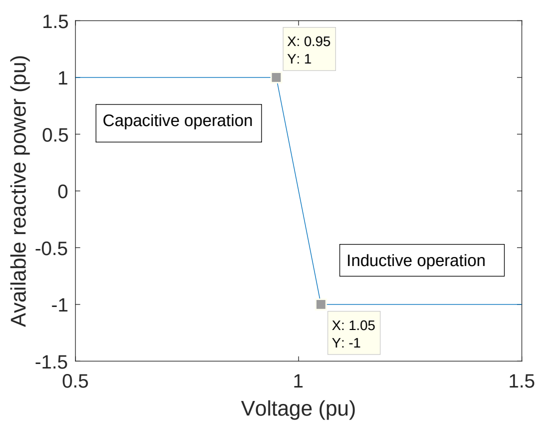

Figure 2: The volt-var curve applied in the PV controllers [16]

A 250 kW, 125 kWh battery bank is installed at bus 860. Battery control is based on peak shaving. It is assumed that the battery bank is fully charged at the start of the simulation. The battery will charge when the PV plant at bus 860 generates more than 0.5 pu and will discharge when it is generating less than 0.5 pu. The key parameters of the battery bank controller are given in Table IV. The regulator parameters remain unchanged from the original study. The installed eight PV plants are given in Table II.

The test case in the OpenDSS format is freely available under the GNU license at https://github.com/RTPIS/DEROpenDSSTestFeeder.

TABLE III: 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

TABLE IV: SPECIFICATIONS OF THE BATTERY BANK

Size (kW)	Capacity (kWh)	Charging rate (%)	Discharging rate (%)	Minimum SOC (%)
250	125	100	100	20

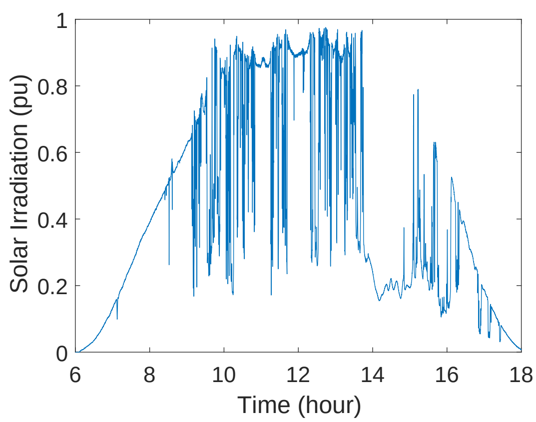

Figure 3: Input solar irradiance profile for simulated 12-hour time period [17]

III. Simulations and Results

This section shows some studies that can be conducted based on the proposed test bed. Since the test bed is ideal for analyzing voltage control, this section provides the examples focused on that specific area. The system performance is compared for five operation modes, spanning from no controls to full control. Full control refers to the case where tap changer (TC), volt-var (VV) and switched capacitor (SC) controllers, and the battery bank (BB), are all connected to the system.

A. Tested Control Strategies

The volt-var scheme shown in Fig. 2 is applied, where it is active. Note that there is no dead band in this scheme. The Solar Irradiation profile shown in Fig. 3 is applied to all the PV systems. Here it is assumed that PV profile does not change between the PV systems that are situated in different locations.

The summarized results for the different cases simulated are given in Table V and VI . The losses here are the total energy loss in the simulated 12-hour time frame. Voltage Mean Squared Error is the total calculated for each of the system nodes. Here, all 95 nodes are used for the calculation to provide a more accurate voltage quality indicator.

1) Test feeder with no controls: In this case, there are no controls applied in the QSTS simulation. Note that both capacitor banks are still connected since it is part of the original IEEE 34 test case. The battery bank is, however, off-line. The resulting state of the system shown in Fig. 4 reinforces the need for voltage control on this system on account of system voltage in some nodes reaching almost 130%.

2) Test feeder with only tap changer controls: The tap changer controls are now activated. The resulting state of the system shown in Fig. 5 reinforces the need for voltage control on this system. In this case, the over-voltage reaches 10% and the total number of tap operations are unacceptably high (tap changer 1 phase A- 1570 tap operations and tap changer 2 phase A 1744 tap operations). Therefore, this operating mode is not acceptable either.

TABLE V: ENERGY LOSS AND MEAN SQUARED ERROR OF THE VOLTAGE PROFILE

Mode	Figure	Energy Loss MWh	V-MSE (pu)
Non	Fig.4	1.36	$6.445\times10^{-}3$
TC	Fig.5	1.39	$1.455\times10^{-}3$
VV	Fig.6	3.50	$1.031\times10^{-}3$
TC+SC	Fig.7	2.03	$1.534\times10^{-}3$
TC+SC+VV	Fig.8	6.14	$1.637\times10^{-}3$
TC+SC+VV+BB (All)	Fig.9	6.07	$1.632\times10^{-}3$

TABLE VI: TAP CHANGER OPERATIONS

Mode	Figure	# of Tap 1A Ops.	# of Tap 2A Ops. #
Non	Fig.4	0	0
TC	Fig.5	1570	1744
VV	Fig.6	0	0
TC+SC	Fig.7	1188	2054
TC+SC+VV	Fig.8	0	136
TC+SC+VV+BB	Fig.9	0	68

3) Test feeder with only volt-var controls: In this case, only volt-var controls are activated. The resulting state of the system is shown in Fig. 6. The system voltage profile has improved over the last two cases, but the system losses have increased. This points out that the choice of volt-var controller replacing the tap changers is a choice for the planner to make based on economic yield. In this case, the increase in losses and ancillary payment to prosumers is the cost and the decrease in all costs associated with voltage regulators is the savings.

4) Test feeder with tap changer and switched capacitor controls: The resulting state of the system is shown in Fig. 7. The results show that the switched capacitors are of no relevance in this case and are always in on-state since the tap changer controls maintain the voltage between 0.95 and 1.05 pu at the capacitor busses. This shows that there is a possibility to improve system performance by using a coordinated control scheme between switched capacitors and the tap changers. Additionally, bus 890 is still operating in an over-voltage state.

5) Test feeder with tap changer, switched capacitor and volt-var controls: The resulting state of the system is shown in Fig. 8. The results show that the system is operating within the voltage limits at all times. In this operational mode, the number of tap changer operations have significantly decreased, whereas the feeder losses have increased.

6) Test feeder with tap changer, switched capacitor, volt-var and battery bank controls: The resulting state of the system is shown in Fig. 9. The results show that the number of tap changer operations have decreased even further in this mode of

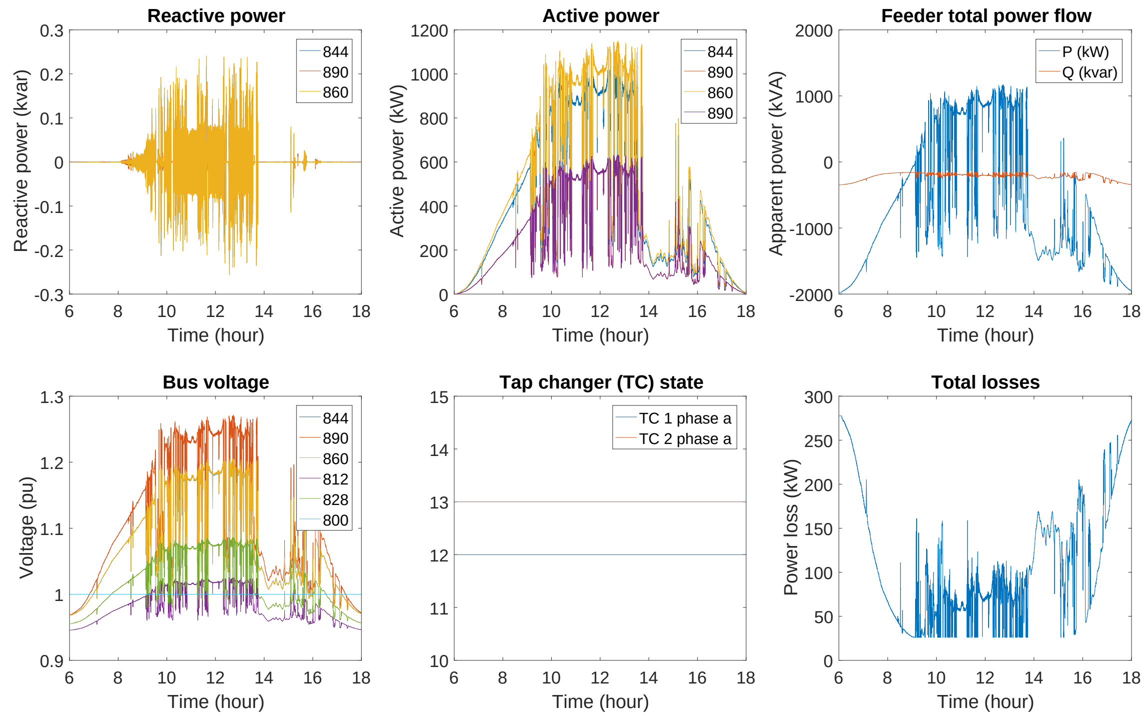

Figure 4: System simulated with all control devices deactivated (capacitor banks are still connected)

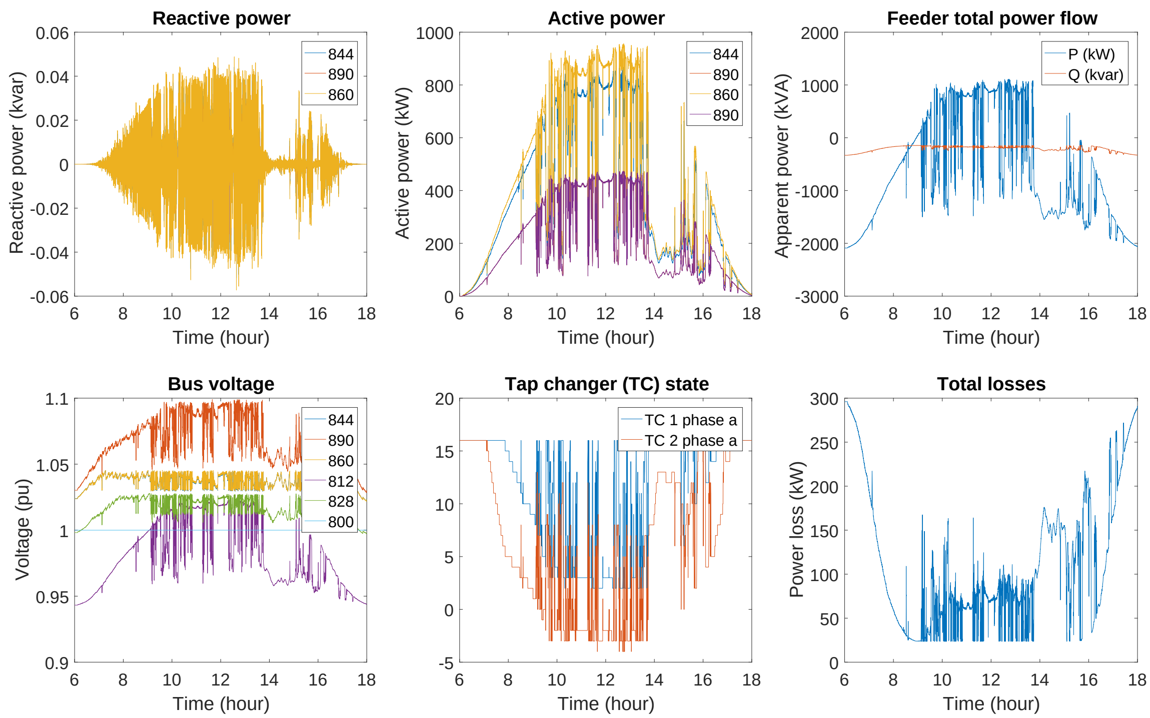

Figure 5: System simulated with only tap changer controls activated

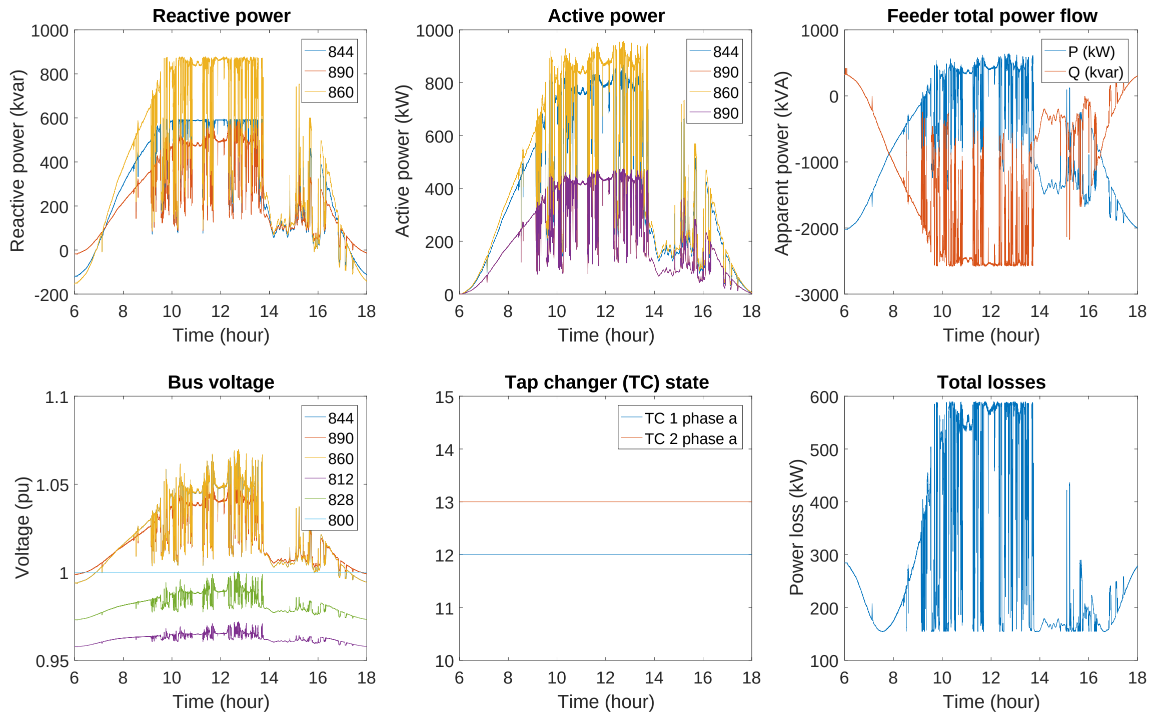

Figure 6: System simulated with only volt-var controls activated

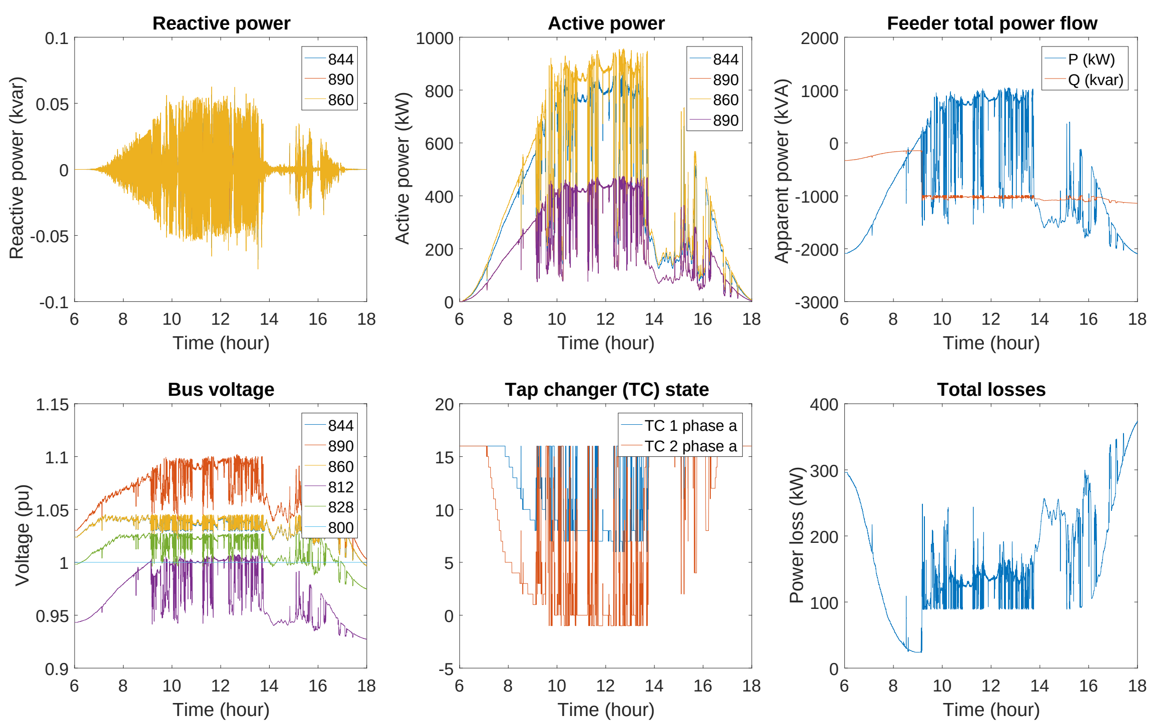

Figure 7: System simulated with activated tap changer and switched capacitor controls but with deactivated volt-var controls

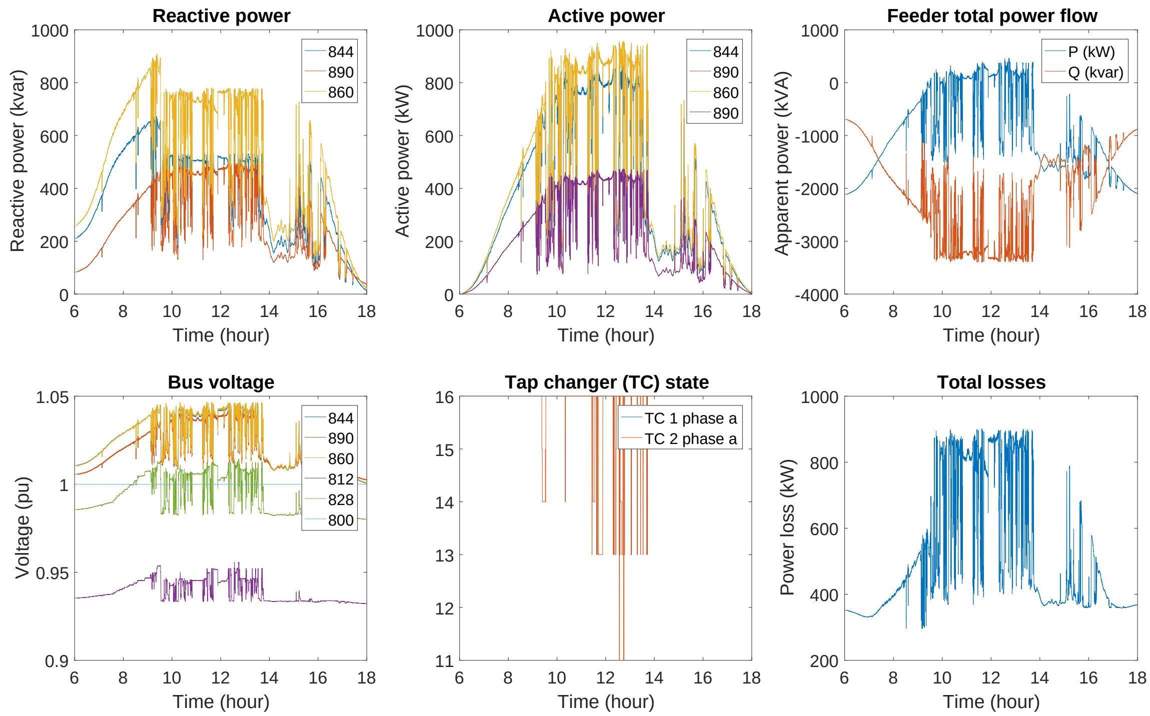

Figure 8: System simulated with tap changer, switched capacitor and volt-var controls

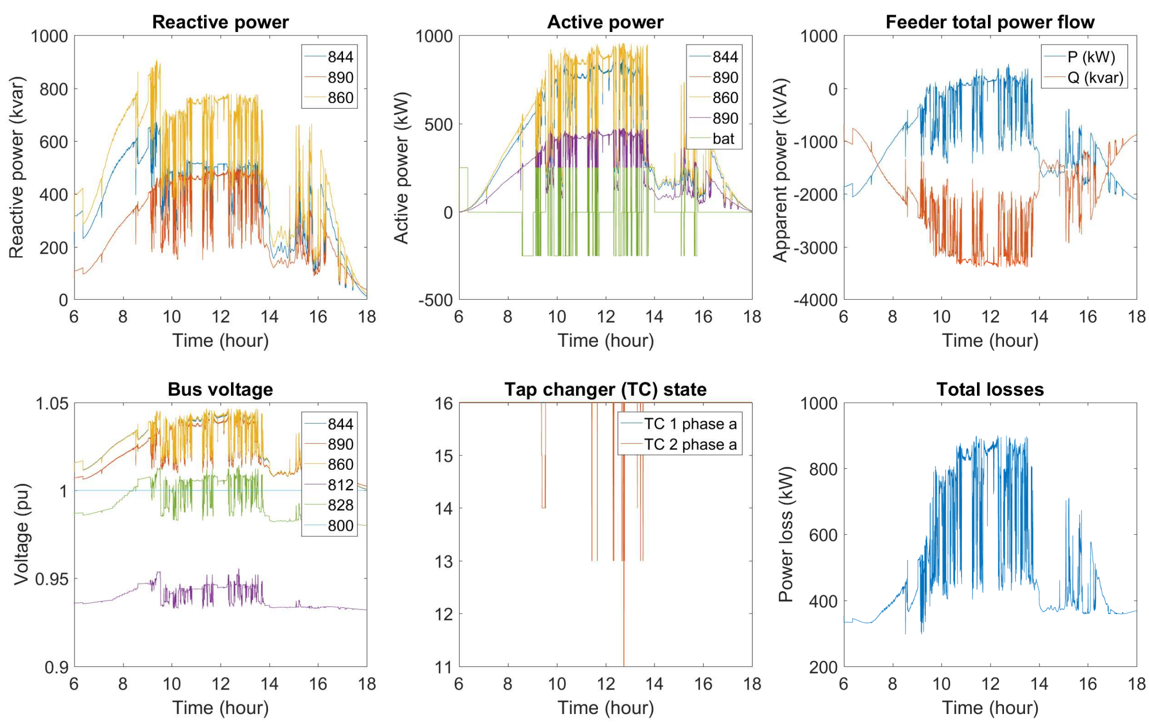

Figure 9: System simulated with tap changer, switched capacitor, battery bank and volt-var controls

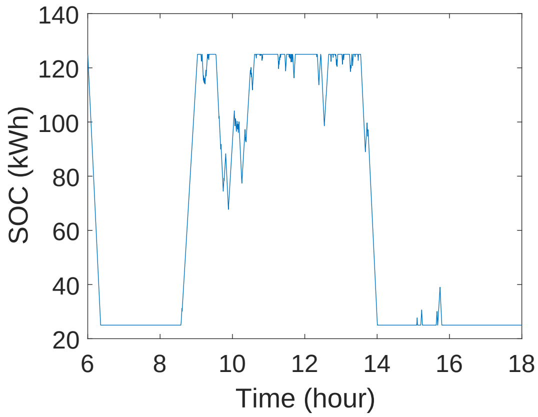

Figure 10: Temporal variation the battery bank state of charge

operation. Additionally, there is a marginal decrease in system total losses as well as in the voltage quality. The resulting SOC profile of the battery bank given in Fig. 10 shows that the battery is not utilized to its maximum potential for peak shaving function.

IV. Conclusion

A distribution feeder test case for DER integration studies has been presented in this paper. The uniqueness of this test feeder is that it has significant DER penetration, reverse power flow and includes all the major components that can be used for control of the modern distribution feeder. The DER connected to this test feeder are operated in grid following mode. The source code for the test feeder is available under the GNU license in GitHub and researchers can use this platform for fast prototyping and development of new control algorithms as well as other DER integration studies. This test feeder model does not include time-varying loads. The inclusion of variability in the loads will serve to enhance the test feeder while increasing the complexity. The introduction time variability can be introduced as a future direction.

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