Application of SVC and Single-Phase Shunt Capacitor to Improve Voltage Profiles and Reduce Losses of Unbalanced Multiphase Smart Grid with PEV Charging Stations

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***Abstract*—In smart grids, the conventional approach of locating compensation devices based on the forecasted daily load curves is not realistic as the locations, times and durations of some loads such as plug-in electric vehicles (PEVs) and smart appliances are randomly changing during the 24 hour period. This paper proposes a new approach to improve the performance of unbalanced multiphase distribution systems consisting of single-, two- and three-phase networks with PEV charging stations. The approach is designated to perform online VRI ranking, place SVCs and single-phase capacitors at the weakest three-phase and single-phase buses, respectively; and then switch these devices in and out of the service according to the lowest voltage ranking index (VRI) values in order to improve voltage profiles and reduce total system losses. Simulation results are performed and compared for an unbalanced multiphase 13 node test feeder with PEV charging stations using DIgSILENT PowerFactory software.**

***Keywords*- smart grid, PEV, charging stations, multiphase, bus voltage ranking and weakest bus.**

I. INTRODUCTION

Plug-in electric vehicles (PEVs) are expected to become popular in the near future as alternatives to conventional fuel-based automobiles in order to reduce the emission to the environment [1-6]. However with the random charging behaviors and unpredictable penetration levels of PEVs in the future residential feeders as well as installation of PEV charging stations in the distribution networks, voltage drop issues and voltage stability problems are anticipated in the future smart grid configurations [1-3, 7]. According to reference [2], PEV charging stations can affect system voltage profile, load flow and stability of the smart grid. Therefore, electric utilities are very interested in investigating the possible impacts and drawbacks of PEV charging demand on the distribution networks [4, 8].

Distribution networks are generally well planned for specific load patterns based on the typical or forecasted daily load curves [9]. However, it will be hard to forecast load patterns in the future smart grid configurations due to the introduction of relatively large PEV loads at the residential feeders with unpredictable charging rates, locations, times and durations; as well as the installation of massive PEV charging stations at the distribution networks. In addition, the high charging power demand due to the fast charging of PEVs can affect transformer loading and system bus voltage profiles. A possible solution is to install compensation devices such as static Var compensators (SVCs) and capacitor banks at the charging stations [10].

Identification of weakest buses through the bus ranking indices will play an important role for the analysis and voltage stability enhancement of smart grids. The purpose of bus ranking in smart grid is to determine which nodes are the weakest buses during the 24 hour period for connecting compensation devices [11]. Furthermore, it can provide insights for properly placing and sizing new PEV charging stations and smart parks. It has been shown that the best locations for reactive power compensation to improve voltage stability margin are the weakest single-, two and three-phase buses [12-13]. In order to obtain the best location of compensation devices, there are several methods based on static approaches to identify the weakest buses in balanced networks. The current bus ranking approaches include modal analysis [14], sensitivity analysis [15], L index [16-17], V/V_0 index [12, 18-19], PV curve [20]. However, the bus ranking problem becomes very complicated under unbalanced and multiphase operating conditions. In term of static voltage stability analysis, all above-mentioned bus ranking indices are only capable of identifying the weakest buses of balanced systems and do not apply to unbalanced and multiphase networks. Therefore, there is much need and high interest to define a reliable bus voltage ranking index (VRI) for unbalanced and multiphase networks that may be used for static and dynamic analyses.

In this paper, symmetrical components are applied to the conventional bus voltage ranking index V/V_0 to extend its application to online identification of the weakest buses of unbalanced multiphase networks. A new approach is implemented to improve the voltage profiles and reduce total losses of the multiphase distribution systems with PEV charging stations. It consists of placement of SVCs and single-phase capacitors at the weakest buses and switching these compensation devices in and out of the service according to the lowest VRI values. Simulation results for the IEEE unbalanced multiphase 13 node test feeder [21] are performed and compared without and with PEV charging stations using DIgSILENT PowerFactory software [22].

II. Identification of Weakest Buses for Placement of Compensation Devices

The approach taken in this study is applying symmetrical components to the conventional bus VRI to identify the weakest three-phase and single-phase buses for placement of SVCs and single-phase shunt capacitors in an hourly basis. This is done to reduce losses and improve voltage profile of the unbalanced multiphase distribution networks with PEV charging stations during the 24 hour period.

The conventional VRI is defined for single-phase and balanced three-phase networks [12, 18-19]:

$$VRI_j^{conventional} = \frac{V}{V_o} = \frac{V_{j,base-load}}{V_{j,no-load}} \qquad (1)$$

where j is the bus number, $V_{j,based-load}$ and $V_{j,no-load}$ are the bus voltages for the base-load and no-load operating conditions, respectively.

To extend and generalize the conventional definition of VRI for unbalanced multiphase networks, symmetrical components are applied to the three-phase voltages resulting from three-phase power flow. The index is defined as the ratio of the positive sequence voltage at base-load to the positive sequence voltage at the no-load [11]:

$$VRI_j^{multiphase} = \frac{V_{j,base-load}^{+}}{V_{j,no-load}^{+}}. \qquad (2)$$

In this paper, Eq. (2) will be used to identify the weakest single-phase and three-phase buses for the placement of single-phase shunt capacitor and SVC units, respectively.

III. Online Placement of SVC Units and Single-Phase Shunt Capacitors to Improve the Performance of Multiphase Systems with PEV Charging Stations

The installation of PEV charging stations at the distribution networks and the population of PEV loads at the residential feeders will deteriorate the performance of smart grid. To overcome this problem, compensation devices can be installed at the weakest buses. However, it will be hard to forecast the load patterns of smart grids due to the unpredictable charging rates, locations, times and durations of the PEVs. Therefore, a new online approach based on the algorithm of Fig. 1 is proposed and implemented in this paper to improve the voltage profiles and reduce total losses of the multiphase distribution systems with PEV charging stations. The approach consists of i) identification of the west buses based on Eq. 2, ii) placement of SVCs and single-phase capacitors at the weakest buses, and iii) switching these devices in and out of the service according to the lowest VRI values.

IV. The IEEE 13 Node Test System with PEV Charging Stations and Compensation Devices

In this paper, the IEEE unbalanced multiphase 13 node test feeder of Fig. 1 [21] is considered with two 0.2MW and four 0.2MW PEV charging stations connected at buses 634 and 680, respectively. The total PEV peak charging (1.2MW) is about 35% of total load (3.46MW). Two SVC units and one single-phase shunt capacitor are first installed according to the lowest VRI values at buses 675, 680 and 611, respectively. The network has been simulated using the DIgSILENT PowerFactory software [22]. The system data and parameters are available in [21]. This unbalanced multiphase 13 node test feeder consists of three-phase (buses 650, RG60, 632, 634, 634, 671, 692 and 675), two-phase (buses 645, 646 and 684) and single-phase (buses 611 and 652) sections with overhead lines, two underground lines (through buses 684, 652 and 692, 675), unbalanced spot loads (Y-PQ, D-PQ, Y-I, D-I, Y-Z, D-Z), distributed loads (Y-PQ) between buses 632 and 671, a single-phase shunt capacitor (at buses 611), a three-phase shunt capacitor (at buses 675), and an in-line transformer (between buses 633 and 634). There is also a three-phase voltage regulator connected between buses 650 and RG60.

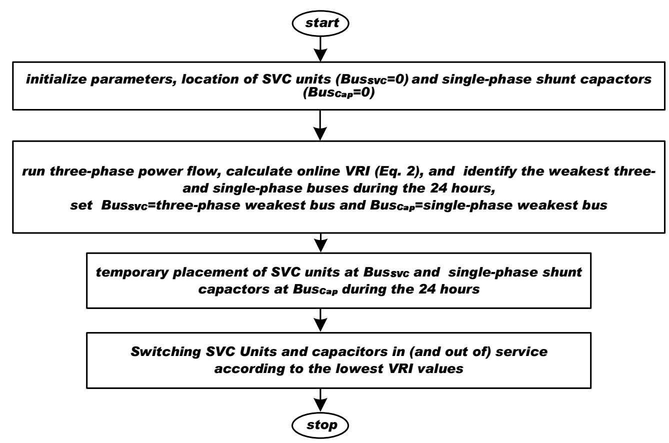


Fig. 1. The proposed algorithm for the online placement of SVC units and single-phase capacitors in multiphase networks with PEV charging stations.

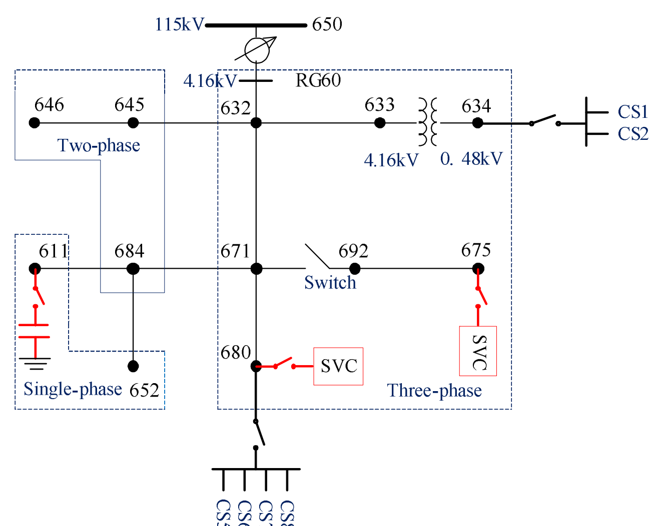
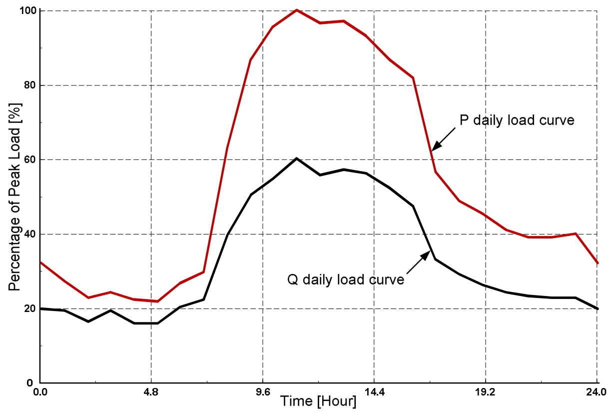
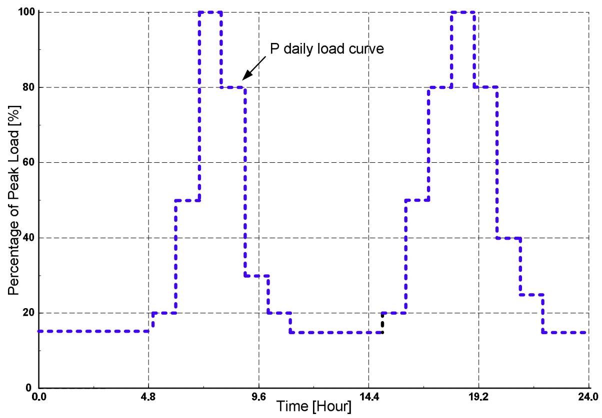


Fig. 2. The simulated IEEE unbalanced multiphase 13 node test feeder with PEV charging stations, SVC units, and a single-phase shunt capacitor [21].

For the dynamic analysis of this paper, the daily P and Q load curves of Fig. 3(a) are assumed for the linear loads [9]. For the PEV charging stations (at buses 634 and 680), the daily load curve of Fig. 2(b) with two peaks at 7am and 6pm is employed [2].



(a)



(b)

Fig. 3. Daily load curves associated with Fig. 1; (a) for linear loads [9], (b) for PEV charging stations [2].

V. Simulation Results

Simulations are firstly performed for the IEEE unbalanced multiphase 13 node test feeder of Fig. 2 [21] without and with PEV charging stations to investigate their impacts on voltage profiles and bus voltage ranking indices. Next, Eq. 2 is used to identify the weakest single- and three-phase buses. Then, the VRIs are calculated and utilized to place SVC units and single-phase shunt capacitors at the weakest three- and single-phase buses, respectively. Finally, the proposed online algorithm of Fig. 1 is used to switch these compensation devices in and out of the service on hourly bases according to the lowest VRI values such that all bus voltage profiles are improved and total system losses are reduce. Simulation results are presented for four case studies.

Case 1: No PEV Charging Stations

The index of Eq. 2 is calculated and ranked to locate the weakest three- and single-phase buses of Fig. 2 without any PEV charging stations. Figure 4 shows the impact of the dynamic daily load curves of Figs. 3(a) and (b) on the voltage profiles of selected nodes (buses 634, 675 and 680). According to this figure, bus 634 has the lowest voltage profile. However the three-phase buses during the 24 hours which have the lowest bus voltage ranking indices are buses 675, 634, and 680. And the single-phase buses which have the lowest VRI are buses 611 and 652. Therefore, the weakest three- and single-phase weakest nodes for Case 1 are buses 675 and 611, respectively. The system active power loss without PEV charging stations is 0.08761MW.

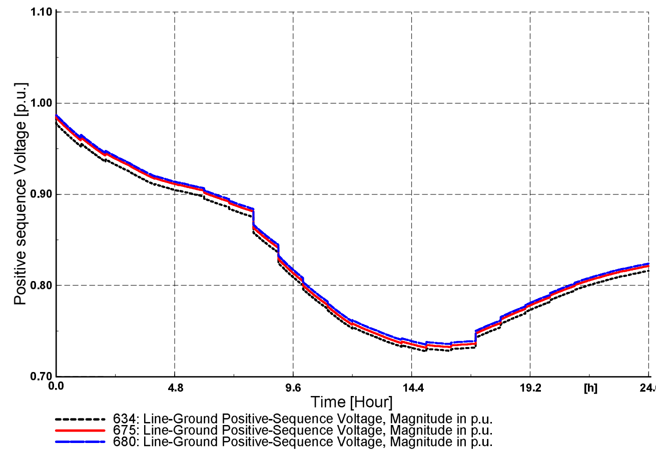


Fig. 4. Simulation results for Case 1: the 24 hour voltage profile of buses 634, 675 and 680

Case 2: Four PEV Charging Stations at Bus 680 and Two PEV Charging Stations at Bus 634

In the multiphase unbalanced system of Fig. 2, four 0.2MW and two 0.2MW PEV charging stations with the daily load curves of Figure 2(b) are placed at bus 680 and 634, respectively. The total peak charging (1.2MW) is about 35% of total load (3.46MW). Figure 5 shows the impact of these charging stations on voltage profiles of buses 634, 675 and 680 during the 24 hour period while Table I shows the bus voltage ranking indices. According to this Table, the locations of the weakest buses have changed between buses 675 and 680. For example, the weakest three-phase node is changed to bus 680 at 7-9 a.m. and 6-9 p.m. The system active power loss with PEV charging stations is increased to 0.26449MW.

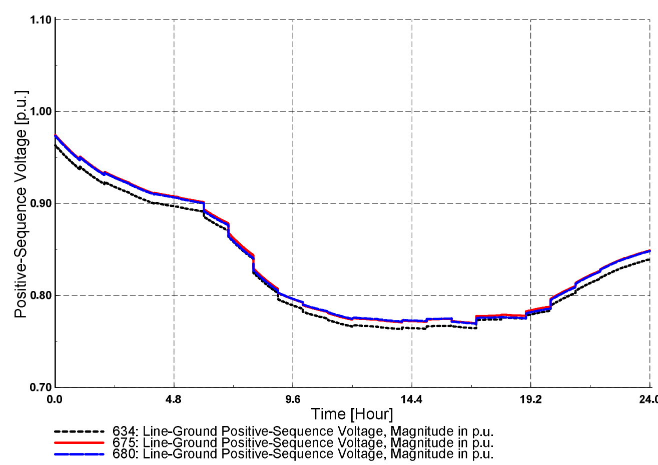


Fig. 5. Simulation results for Case 2: the 24 hour voltage profile of buses 634, 675 and 680.

Case 3: Online Placement of SVC Units for Case 2.

The proposed algorithm of Fig. 1 will be demonstrated by placing only SVC units (rated at 0.36 MVar and acting as an unbalanced voltage controllers) at the weakest three-phase buses, performing online VRI ranking, and then switching

SVCs in and out of the service according to the lowest VRI values.

Online VRI ranking of the unbalanced multiphase 13 node test feeder with four PEV charging stations at bus 680 and two PEV charging stations or bus 634 (Case 2) indicates that the weakest three-phase bus changes between nodes 675 and 680 over the 24 hour period (Table I). Therefore, two SVC units which are installed at buses 675 and 680 will be switched on and off according to the time intervals of Table I.

Figure 6 shows the impact of online placement of two SVC units on voltage profiles with four PEV charging stations at bus 680 and two PEV charging stations at bus 634. Compared to Case 2 (Figure 5), the voltage profiles are improved, especially at buses 675 and 680. Table II shows the bus voltage ranking indices after the online placement of SVC units installed at bus 675 and 680. According to this Table, the weakest three-phase node (after online SVC placement) is changed from buses 675 and 680 to bus 634. The system active power loss for Case 3 is reduced from 0.26449MW to 0.25721MW.

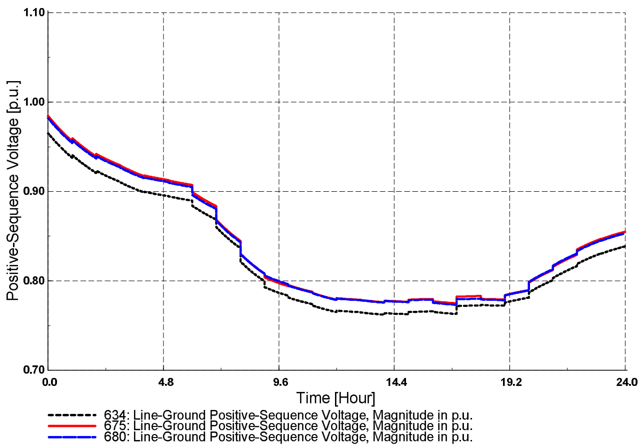


Fig. 6. Simulation results for Case 3 with online placement of two SVC units: the 24 hour voltage profile of buses 634, 675 and 680.

Case 4: Online Placement of SVC Units and Single-Phase Shunt Capacitors for Case 2.

The proposed algorithm of Fig. 1 will be demonstrated by online placement of both SVC and capacitor banks in the IEEE unbalanced multiphase 13 node test feeder of Fig. 2.

Online VRI ranking of the unbalanced multiphase 13 node test feeder with four PEV charging stations at bus 680 and two PEV charging stations or bus 634 (Case 2) indicates that the weakest three-phase bus changes between nodes 675 and 680 and the single-phase weakest bus remained at bus 611 over the 24 hour period (Table I). Therefore, two SVC units which are installed at buses 675 and 680 and a single-phase shunt capacitors which is installed at buses 611 will be switched on and off according to the time in Table I. According to Fig. 7, the voltage profiles at buses 675 and 680 are improved while the system active power loss is reduced to 0.25135MW.

TABLE I. CASE 2 - VRI FOR THE MULTIPHASE SYSTEM OF FIG. 1 WITH FOUR PEV CHARGING STATIONS AT BUS 680 AND TWO PEV CHARGING STATIONS AT BUS 634.

Time [hour]	VRI (Eq. 2) at Bus 634	VRI (Eq. 2) at Bus 675	VRI (Eq. 2) at Bus 680	Weakest bus	
				1p	3p
0:00	0.980186	0.969367	0.969430	611	675
1:00	0.931868	0.919640	0.920164	611	675
2:00	0.915040	0.903259	0.903690	611	675
3:00	0.904979	0.893448	0.893767	611	675
4:00	0.892726	0.881386	0.881763	611	675
5:00	0.888124	0.876815	0.877107	611	675
6:00	0.882623	0.871067	0.871200	611	675
7:00	0.861427	0.847999	0.847394	611	680
8:00	0.830174	0.813725	0.811798	611	680
9:00	0.792331	0.777062	0.776437	611	680
10:00	0.774322	0.761940	0.763098	611	675
11:00	0.762916	0.751094	0.752668	611	675
12:00	0.753490	0.742078	0.743883	611	675
13:00	0.752773	0.741401	0.743099	611	675
14:00	0.749586	0.738288	0.740013	611	675
15:00	0.749811	0.738618	0.740282	611	675
16:00	0.752786	0.741394	0.742800	611	675
17:00	0.749838	0.736729	0.737238	611	675
18:00	0.759273	0.744732	0.743968	611	680
19:00	0.760036	0.744424	0.742983	611	680
20:00	0.768626	0.754182	0.753168	611	680
21:00	0.787815	0.775682	0.775632	611	680
22:00	0.803453	0.792100	0.792427	611	675
23:00	0.816681	0.805766	0.806365	611	675

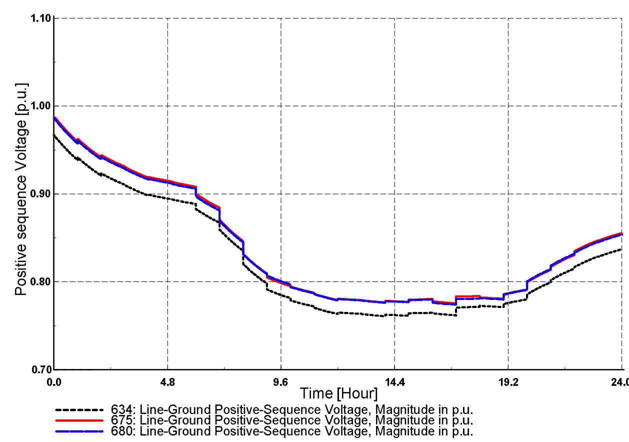


Fig. 7. Simulation results for Case 4: the 24 hour voltage profile of buses 634, 675 and 680.

TABLE II. CASE 3 VRI VALUES FOR MULTIPHASE SYSTEM OF FIG. 1 (WITH FOUR AND TWO PEV CHARGING STATIONS AT BUSES 680 AND 634) AFTER ONLINE PLACEMENT OF TWO SVC UNITS.

Time [Hour]	VRI (Eq. 2) at Bus 634	VRI (Eq. 2) at Bus 675	VRI (Eq. 2) at Bus 680	Three-phase weakest bus
0:00	0.998229	1.007018	1.003504	634
1:00	0.901377	0.918712	0.919228	634
2:00	0.885086	0.902328	0.902751	634
3:00	0.875946	0.893086	0.893397	634
4:00	0.864844	0.881851	0.882220	634
5:00	0.861389	0.878238	0.878524	634
6:00	0.854892	0.872471	0.872597	634
7:00	0.823465	0.845201	0.844589	634
8:00	0.774945	0.80296	0.801047	634
9:00	0.744331	0.767646	0.767017	634
10:00	0.744796	0.760438	0.761584	634
11:00	0.741155	0.755132	0.756705	634
12:00	0.737111	0.750354	0.752172	634
13:00	0.739296	0.752539	0.754253	634
14:00	0.737999	0.751276	0.753022	634
15:00	0.739474	0.752874	0.754561	634
16:00	0.741581	0.755811	0.757236	634
17:00	0.729233	0.747394	0.747900	634
18:00	0.726917	0.749654	0.748874	634
19:00	0.718291	0.743732	0.742282	634
20:00	0.729811	0.752813	0.751791	634
21:00	0.760041	0.778158	0.778101	634
22:00	0.781170	0.797583	0.797903	634
23:00	0.798652	0.813863	0.814459	634

TABLE III. CASE 3 VRI VALUES FOR MULTIPHASE SYSTEM OF FIG. 1 (WITH FOUR AND TWO PEV CHARGING STATIONS AT BUSES 680 AND 634) AFTER ONLINE PLACEMENT OF TWO SVCS AND SINGLE-PHASE SHUNT CAPACITORS.

Time [hour]	VRI (Eq. 2) at Bus 634	VRI (Eq. 2) at Bus 611	VRI (Eq. 2) at Bus 652	Weakest bus	
				1p	3p
0:00	0.986850	0.999097	0.963478	652	634
1:00	0.920957	0.892312	0.897544	611	634
2:00	0.903613	0.876757	0.881371	611	634
3:00	0.893516	0.868665	0.8721	611	634
4:00	0.881412	0.855862	0.860176	611	634
5:00	0.877212	0.853136	0.856258	611	634
6:00	0.872021	0.847695	0.850803	611	634
7:00	0.851107	0.821948	0.827023	611	634
8:00	0.819673	0.793987	0.786257	652	634
9:00	0.783230	0.750089	0.749335	652	634
10:00	0.766949	0.732645	0.735348	611	634
11:00	0.757580	0.714324	0.730644	611	634
12:00	0.749144	0.704943	0.722327	611	634
13:00	0.749304	0.706723	0.722976	611	634
14:00	0.746643	0.703663	0.720302	611	634
15:00	0.747265	0.70511	0.721326	611	634
16:00	0.750504	0.709711	0.724842	611	634
17:00	0.747610	0.706142	0.720258	611	634
18:00	0.757021	0.719848	0.729755	611	634
19:00	0.756855	0.728041	0.723985	652	634
20:00	0.765439	0.739613	0.734274	652	634
21:00	0.784607	0.763421	0.756649	652	634
22:00	0.799901	0.780322	0.772977	652	634
23:00	0.813405	0.785935	0.791883	611	634

VI. CONCLUSION

This paper proposes a new approach for the online placement of SVC units and single-phase capacitors to improve the performance of unbalanced multiphase smart grid with PEV charging stations. The approach is demonstrated on an unbalanced multiphase 13 node test feeder using DIgSILENT PowerFactory software. Main conclusions are:

- Online bus voltage ranking approaches are required in smart gird systems as the locations of the weakest buses will change over the 24 hour period and the PEV charging stations with relatively large power ratings can have detrimental impacts of smart grid loading, losses and voltage profiles.
- The proposed algorithm of Fig. 1 can be utilized to perform online VRI ranking, place compensation devices, and then switch these devices in and out of the service to improve voltage profiles and reduce losses.
- The performance of unbalanced multiphase smart grid can be improved by switching SVCs and shunt capacitors at the weakest three-phase and single-phase buses according to the lowest VRI values.

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VIII. Biographies

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