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Combined Optimal Capacitor Placement and Network Reconfiguration in A Distribution Power System for Load Flow Analysis Using ETAP

***Abstract**. It is necessary to determine the system's characteristics to operate an electrical power distribution system under stable conditions. Load flow analysis is a technique that can be used to determine these characteristics and study power systems under various conditions. Regarding the construction of the distribution system, distribution companies are looking for techniques to optimize the performance of their systems. The major problem distribution companies face undervoltage caused by the increased load. Practical techniques for overcoming the undervoltage problem and minimizing system losses are optimal reconfiguration and capacitor placement (OCP). This paper uses the Electrical Transient Analyzer Program (ETAP) to design the IEEE 33-bus radial distribution test system. The combination of optimal capacitor placement and reconfiguration is used to analyze and optimize the radial distribution test system effectively to avoid the undervoltage problem and minimize power losses.*

Streszczenie.** Określenie charakterystyk systemu jest niezbędne do pracy systemu rozdziału energii elektrycznej w stabilnych warunkach. Analiza przepływu obciążenia jest techniką, której można użyć do określenia tych charakterystyk i zbadania systemów zasilania w różnych warunkach. Jeśli chodzi o budowę systemu dystrybucyjnego, firmy dystrybucyjne poszukują technik optymalizacji wydajności swoich systemów. Główne firmy dystrybucyjne borykają się z niskim napięciem spowodowanym zwiększonym obciążeniem. Praktyczne techniki radzenia sobie z problemem zbyt niskiego napięcia i minimalizowania strat w systemie to optymalna rekonfiguracja i rozmieszczenie kondensatorów (OCP). W tym artykule wykorzystano program Electrical Transient Analyzer Program (ETAP) do zaprojektowania radialnego systemu testowego dystrybucji szyn IEEE 33. Połączenie optymalnego rozmieszczenia kondensatorów i rekonfiguracji służy do skutecznej analizy i optymalizacji systemu testowego dystrybucji promieniowej w celu uniknięcia problemu zbyt niskiego napięcia i zminimalizowania strat mocy.* (Połączone optymalne rozmieszczenie kondensatorów i rekonfiguracja sieci w systemie dystrybucji zasilania do analizy przepływu obciążenia z wykorzystaniem ETA***)

Keywords: Optimization; Load Flow Analysis; Network Reconfiguration; Optimal Capacitor Placement (OCP); ETAP
Słowa kluczowe: Analiza przepływu obciążenia; Optymalne rozmieszczenie kondensatorów (OCP); Rekonfiguracja sieci; Optymalizacja; ETAP

Introduction

The load flow solution is essential for evaluating and operating a real electrical distribution system. It allows us to validate the sizing of cables, switchgear, and transformers and determine the real (kW) and reactive (kvar) power losses at the nodes' different branches, magnitudes, and voltage angles. Load flow studies were conducted to obtain suitable voltage profiles and loss rates under other operational conditions and low and high load. Various approaches are used to remedy the problem of high losses rates, such as reconfiguration, optimal placement of capacitors, optimal placement of distributed generation, and optimal use of electrical equipment. The load flow analysis is also a starting point for other system studies [1-2].

To validate the selected sizing of transformers, switching devices, and transmission cables, load flow analysis is necessary to determine the appropriate voltage profile under various operational situations, for example, high and low load conditions. Load flow analysis is required to determine the capacitor's optimal size and placement to correct the power factor. The load flow analysis results are used as a starting point for further power system analysis [3]. Managing and optimizing the electrical distribution system (i.e., state estimation, VAR planning, etc.) calls for quick, efficient, and repetitive load flow solutions. [4] Load flow analysis requires, first of all, determining all node voltages. The results of the voltages were brought back to determine the currents that circulate in the different branches, the power flows, the system's losses, and other quantities in a steady state. [5] In the operating standards of an electrical distribution network, the voltage supplied to the consumer must vary by +/- 5 percent from the nominal value. The voltage drop causes a reactive power flow (vars); for this reason, undervoltage is a critical problem in all public utility systems. The first quick fix is the RDS reconfiguration system, which involves changing the grid structure by switching the state of the opened and closed switches, considering the demand profile of the different consumers and the supply of all clients. [6-7] However, in some situations where the loading conditions are significant, the objective is not to reach 100%, so we move to the second solution, which is to generate the reactive powers near the consumer side with the location of the optimal capacities.

In this paper, using ETAP (Electrical Transient Analyzer Program) to provide reliable and accurate results in realizing the IEEE 33-bus distribution power system, we combine optimal capacitor placement and reconfiguration to analyse and optimize the IEEE 33-bus distribution power system to overcome the problem of under voltage and minimize the losses. Once an optimal topology is obtained for the different power conditions and the optimal capacitor locations are achieved, the system voltage profile is enhanced, and the losses are minimized, which leads to an improved and stable system.

Radial distribution system

The radial structure is widely used in power distribution networks in long-distance rural zones with low populations or with consumers feeling remote. This network architecture is less reliable but cost-effective than other structures (Ringed, Grid...). In the radial distribution system, we have a single power source with multiple distribution nodes at one end connected by branches. [8] The energy distributed in a radial architecture system is delivered from a source HTB/HTA transformer substation to the main branch to the sub-branches arriving at HTA/HTA or HTA/BT transformers substation nodes. The energy is divided again from the sub-branches, Fig. 1. The radial distribution power system nodes are connected to the source by various channels. The radial system can be operated in multiple topologies depending on the load and the incident. [9]

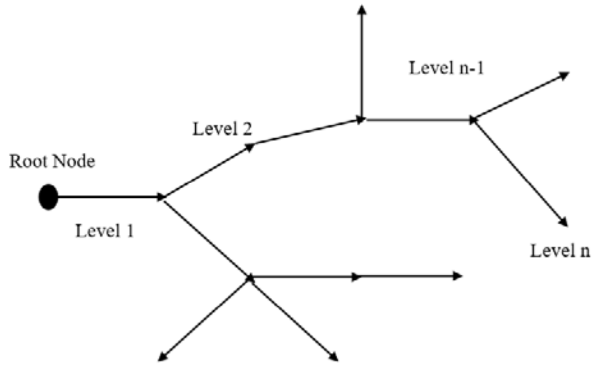

Fig.1. Structure of the radial distribution power grid

The numbering of nodes and lines is based on the following criteria:

1. Nodes are numbered in ascending order sequentially, starting from layer to layer so that every route from the top node to an end node intersects with nodes numbered in ascending sequence.
2. Every path begins at the source node (root side) and is marked by the node number of its unique destination node. [10]

Problem formulation

Analysing an electrical distribution system with a radial structure begins with studying the load flow. The technique permits us to determine the system's characteristics in different operating conditions. The results obtained help us to carry out other studies on the network. The load flow analysis aims to determine the network's power loss factor (real and reactive power losses of the different branches, and the corresponding voltage profiles (node magnitude and voltage angle). In Fig. 2, we consider a section of a distribution network represented by 2 nodes, *k*, and *k+1*, connected by the branch *l*.

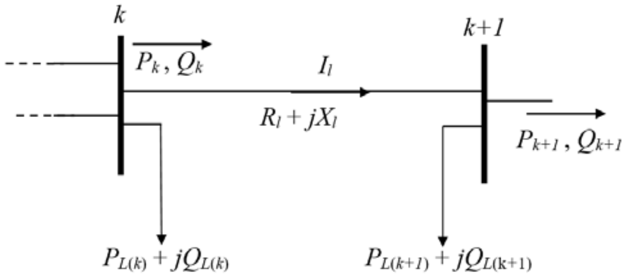

Fig.2. Diagram of a two-node distribution line

- P_k and Q_k are the flowing active and reactive power in the branch *l* from node k to node *k+1*.
- $P_{L(k+1)}$ and $Q_{L(k+1)}$ are the loads' real power and reactive power at node *k+1*.
- $P^{loss}_{(k,k+1)}$ and $Q^{loss}_{(k,k+1)}$ are the real and reactive power loss in the connected line buses *k* and *k+1*, which can be calculated as follows:

$$P_{(loss(k,k+1))} = R_{(k)} \frac{P_{(k)}^2 + Q_{(k)}^2}{V_{(k)}^2} \tag{3}$$

$$Q_{(loss(k,k+1))} = X_{(k)} \frac{P_{(k)}^2 + Q_{(k)}^2}{V_{(k)}^2} \tag{4}$$

To find the system's total power, PT, loss by adding up the power loss of all the outputs of the system:

$$P_{(T,loss)} = \sum\nolimits_{(k=1)}^{n} P_{(loss(k,k+1))} R_{(k)} \tag{5}$$

$$Q_{(T,loss)} = \sum\nolimits_{(k=1)}^{n} Q_{(loss(k,k+1))} R_{(k)} \tag{6}$$

- P(T,loss) and Q(T,loss) are the total real and reactive power losses.

2- To calculate the amplitudes and voltage angle of the nodes going from the source node to the final node in the forward direction. [11]

$$I_{(l)} = \frac{\left(V_{(k)}\angle\delta_{(k)} - V_{(k+1)}\angle\delta_{(k+1)}\right)}{R_{(l)} + jX_{(l)}} = \frac{P_{(k)} - jQ_{(k)}}{V_{(k)}\angle\delta_{(k)}} \tag{7}$$

$$\begin{gathered} V_{(k)}^2 - V_{(k)}V_{(k+1)}\angle(\delta_{(k+1)} + \delta_{(k)}) = \\ (P_{(k)} - jQ_{(k)})(R_{(l)} + jX_{(l)}) \end{gathered} \tag{8}$$

- $V_k \angle \delta_k$: Voltage amplitude and the angle at the k-node
- $V_{k+1} \angle \delta_{k+1}$: Amplitude and angle of the voltage at node *k1*.
- I_l: The flowing current in the branch *l*.
- $Z_l = R_l + jX_l$: Connected impedance from k to *k+1*.

By assimilating the two real and imaginary parts of equation (8):

$$\begin{gathered} V_{(k)}V_{(k+1)}\cos(\delta_{(k+1)} - \delta_{(k)}) = \\ V_{(k)}^2 - (P_{(k)}R_{(l)} + Q_{(k)}X_{(l)}) \end{gathered} \tag{9}$$

$$\begin{gathered} V_{(k)}V_{(k+1)}\sin(\delta_{(k+1)} - \delta_{(k)}) \\ = Q_{(k)}R_{(l)} - P_{(k)}X_{(l)}) \end{gathered} \tag{10}$$

Square and add equation (9) to (10):

$$\begin{gathered} (V_{(k)}V_{(k+1)})^2 = \left[V_{(k)}^2 - (P_{(k)}R_{(l)} + Q_{(k)}X_{(l)})\right]^2 \\ + \left[Q_{(k)}R_{(l)} - P_{(k)}X_{(l)}\right]^2 \end{gathered} \tag{11}$$

$$\begin{gathered} (V_{(k)}V_{(k+1)})^2 = V_{(k)}^4 - 2V_{(k)}^2(P_{(k)}R_{(l)} + Q_{(k)}X_{(l)}) \\ + ({R_{(l)}}^2 + {X_{(l)}}^2)({P_{(k)}}^2 + {Q_{(k)}}^2) \end{gathered} \tag{12}$$

$$V_{(k+1)} = \begin{bmatrix} V_{(k)}^2 - 2(P_{(k)}R_{(l)} + Q_{(k)}X_{(l)}) \\ + ({R_{(l)}}^2 + {X_{(l)}}^2)\dfrac{({P_{(k)}}^2 + {Q_{(k)}}^2)}{V_{(i)}^2} \end{bmatrix}^{1/2} \tag{13}$$

The angle of voltage, δk+1, is found by sharing equations (10) and (9)

$$\begin{gathered} \tan\left(\delta_{(k+1)} - \delta_{(k)}\right) = \\ \frac{\left(Q_{(k)}R_{(l)} - P_{(k)}X_{(l)}\right)}{\left[V_{(k)}^2 - (P_{(k)}R_{(l)} + Q_{(k)}X_{(l)})\right]} \end{gathered} \tag{14}$$

$$\begin{gathered} \delta_{(k+1)} = \delta_{(k)} + \tan^{-1} \\ \frac{\left(Q_{(k)}R_{(l)} - P_{(k)}X_{(l)}\right)}{\left[V_{(k)}^2 - (P_{(k)}R_{(l)} + Q_{(k)}X_{(l)})\right]} \end{gathered} \tag{15}$$

Optimal capacitor placement (OCP) using ETAP: system design with ETAP

ETAP Power Station [12] is a program for the analysis of electrical systems that is fully graphical. ETAP Power Station uses a genetic algorithm approach for optimal capacitor placement. The distribution networks which pose a low power factor problem because of the loads and distribution equipment result in voltage drop and losses growth [13]-[16]. To remove these problems, it is necessary to place shunt capacitors in the electrical systems knowing: 1. the bank's capacity in kvar, 2. the location, 3. the control method, and 4. The type of coupling (Y or Δ). The companies want to solve the distribution network while respecting the constraint with minimum cost. This is the problem of optimization. There are various optimization approaches for this problem, in this work using ETAP software equipped with a powerful simulation module ETAP OCP. The OCP module searches for optimal capacitor placement and battery size to enhance the voltage profile, power factor correction, and savings during the planning period by reducing VAR losses at a minimal total cost. The graphical interface allows the possibility to control the capacitor placement process. The OCP uses a present-value approach to compare alternatives. It considers initial installed and operational costs, including repair, amortization, and reduction of power losses. It also takes into account the interest rate and inflation.

Results and discussion

A. ETAP alignments during load flow simulation

The ETAP software uses the adapted Newton-Raphson method to solve the load flow problem [18]-[20]. After analysis of the load flow in the IEEE 33 bus system, we can find voltage drops from node 6 at 94.948% level to 90.381% level at node 18 and from node 26 at 94.755% to 91.641% at node 33, which is noticeable in Fig. 4.

After performing the load flow simulation, a summary analysis report shows how much the system requires emergency support. It can be seen clearly that the 6-18 and 26-33 buses are running at a lower voltage as shown in Table 3.

The objective function for grid reconfiguration

The aim is to reduce the operational losses in the distribution systems and thus improve the system voltage profile. For this, finding the optimal set of switching branches is necessary so that the next distribution system has the lowest active losses and the optimal voltage profile. The problem's mathematical model can be formulated as follows. Equation (16) has the first expression as the total power losses in the grid, and the second expression is the voltage deviation index [9].

$$\text{(16)} \qquad \mathit{Minimize}\ (\mathrm{F}) = \sum_{(i=1)}^{n} P_{(ij(loss))} \sqrt{\frac{\sum_{(i=1)}^{(NVB)} (V_{(Li)} - V_{(L)})^2}{N}}$$

$$\text{(17)} \qquad V_{(\min)} \le \left|V_{(i)}\right| \le V_{(\max)}$$

Methodology

The simulated system under ETAP is an IEEE 33-bus model, as presented in Fig. 3. The modeling of the transmission lines is in the nominal π model. The real and reactive power of the loads are assumed to be constant values. The distribution system has a radial structure, so the current and power transmitted are directional from the substation to the loads. The failure or destruction of equipment results in a blackout in the downstream power system. Therefore, the availability and reliability of transmission lines and equipment is a concern that requires companies and utilities to take specific steps to enhance the system's performance. [17] The voltage profile gets degraded from the source to the loads and the current increases in the load to the source. A more considerable R/X value means that the electrical system is poorly conditioned and that classical load flow methods could be more effective in resolving the load flow problem.

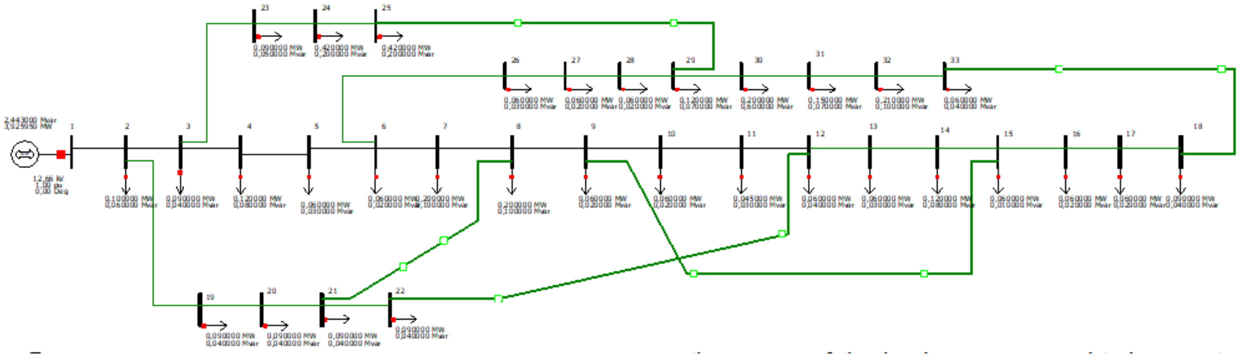

Fig.3. Single line diagram of 33 bus test system

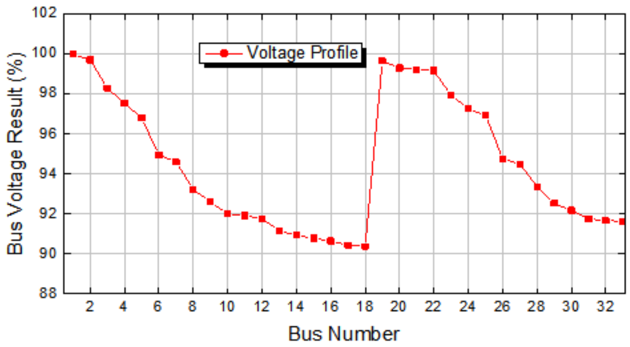

Fig.4. Base case voltage profile of the IEEE 33-Bus radial distribution power system

B. System reconfiguration and load flow analysis

The IEEE 33-Bus radial distribution power system has the same link line considered open 33, 34, 35, 36, 37. According to the findings derived from the load flow study in the previous step, we have the following data: the actual power load is 3715 kW in total, the losses are 210.950 kW, and the minimal voltage is 90.381 p.u at bus 18.

The optimal reconfiguration using the proposed method is achieved by ETAP with the connection switches 33, 34, 35, and 36 closed and the isolators 7, 9, 14, and 32 are open. This new reconfiguration is the most optimal according to the load flow analysis of the new reconfiguration: the losses are reduced to 123.606 kW, which is a reduction of 87.3441 kW of the active power losses, the least favorable voltage is 95.318 p.u at bus 32, and it is also within the voltage limits as shown in Fig. 5.

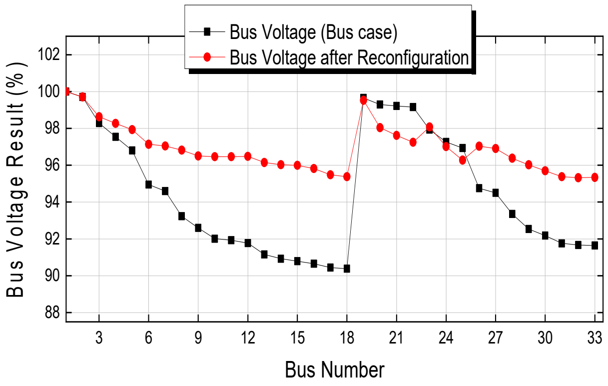

Fig.5. Comparative voltage profile after reconfiguration results

C. Capacitor placement and load flow analysis simulation

The voltage drop problem of the IEEE 33-bus system is solved under ETAP by the optimal capacitor. Fig. 6 shows that the voltage profile has not been drop below 95%.

Table 1 shows the required location of capacitor banks. Capacitors are utilized to provide reactive power for effective transmission line power flow.

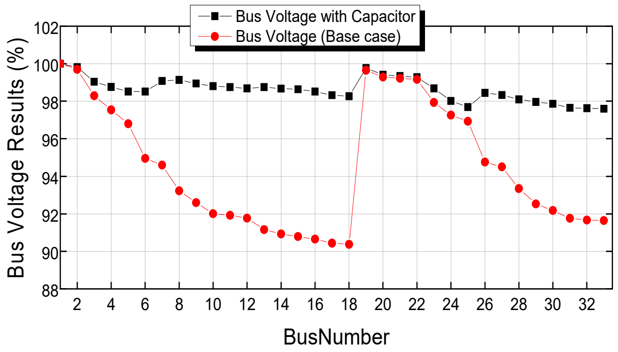

Fig.6. Comparative voltage profile with capacitors results

Fig. 6 shows that the problem of voltage drop is solved after the placement of the capacitor banks of 300MVAR in seven buses at different numbers, following the example at bus 32, a capacitor of 300MVAR, and at bus 30, a capacitor of 300MVAR. As a result, the load flow through the power grid is efficient due to reduced losses.

The summarized report after the capacitors are located at the appropriate location in the grid gives a power factor of 92.78% throughout the system. But this solution is expensive because of the large installed capacitor banks in the system.

Table 1. Optimal capacitor Placement Results

Bus N°	Volt kV	Volt Mag	Volt Ang	Per PF	Rated kVar Bank	Rated kV	Num Banks
7	12.66	97.59	-3.38	-48.9	300	13.80	2
8	12.66	97.25	-4.64	-32.5	300	13.80	3
13	12.66	96.29	-6.20	-14.3	300	13.80	2
15	12.66	96.07	-6.45	-27.3	300	13.80	1
26	12.66	97.01	-3.02	-29.3	300	13.80	1
30	12.66	95.72	-4.05	-58.2	300	13.80	4
32	12.66	95.34	-4.31	-87.1	300	13.80	1

D. Combined reconfiguration and OCP

In this step, we combine reconfiguration and OCP to find an optimal configuration to save capacitors, the simulation results are shown in Fig. 7.

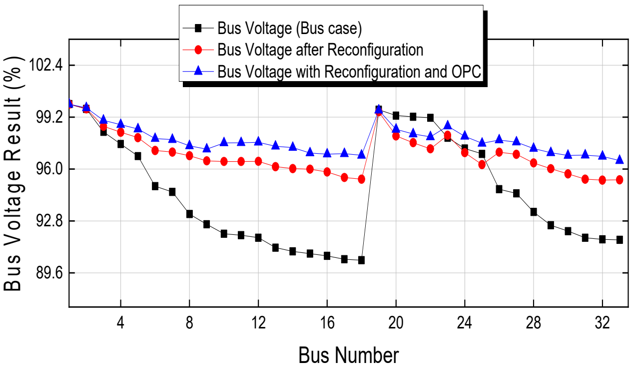

Fig.7. Comparative voltage profile results

Therefore, the optimization process starts with the reconfiguration and finishes with the capacitor placement. For reconfiguration, the re-configured power system was taken into consideration for the OCP as shown in Table 2.

Table 2. Optimal capacitor placement with reconfiguration results

Bus N°	kV	Volt Mag	Volt Ang	Rated kVar Bank	Rated kV	Num Banks
4	12,660	98.300	-0.26	300,00	13.800	1
12	12,660	96.676	-1.56	300,00	13.800	1
17	12,660	95.566	-2.49	300,00	13.800	1
24	12,660	97.329	-0.52	300,00	13.800	1
30	12,660	95.552	-0.89	300,00	13.800	1
31	12,660	95,474	-1.18	300,00	13.800	2

The proposed approach decreases energy losses from 210.950 kW to 120.642 kW and keeps the node's voltages far beyond the minimal value. Comparing the capacitors placed before and after reconfiguration, it is noticed that the number is decreased, thus less troubleshooting and more efficiency as shown in Fig.8.

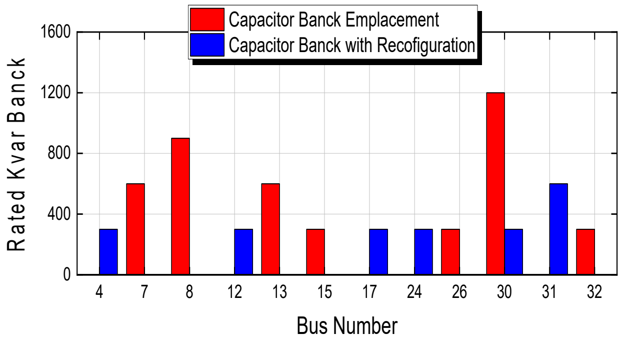

Fig.8. Comparative capacitor placement before and after reconfiguration

Conclusions

Power flow analysis is essential to evaluate an existing system's different operating states. The problem of undervoltage is reduced by locating capacitors in appropriate locations/buses. A load flow analysis is performed using ETAP software based on a technique to overcome the undervoltage problem in an IEEE 33-bus radial distribution power system. Load flow analyses can be utilized to assess the optimal capacitor size and location to overcome the undervoltage problem. Furthermore, they are valuable in determining the power system voltage during unexpectedly high applied or disconnected load conditions. The utilities may also find the proposed simulation analysis helpful in power systems planning and improvement.

Table 3. Critical report results

Bus	10	11	12	13	14	15	16	17	18
KV	11.64	11.63	11.61	11.54	11.51	11.49	11.47	11.45	11.42
Mag	92.00	91.92	91.77	91.15	90.92	90.78	90.64	90.44	90.38
Bus	26	27	28	29	30	31	32	33	
KV	11.99	11.96	11.81	11.71	11.67	11.61	11.60	11.60	
Mag	94.75	94.49	93.35	92.53	92.17	91.76	91.69	91.64	
Bus	6	7	8	9					
KV	12.02	11.97	11.80	11.72					
Mag	94.94	94.59	93.23	92.59					
Alert	Under Voltage								

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