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Voltage Profile Improvement through Load Shedding Action Using Linear Programming-based Optimal Power Flow

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***Abstract*—**This paper proposes a load shedding scheme to improve voltage profile of a power system. A linear programming approach to optimal power flow is utilized to obtain optimum amount of load to shed in order to bring power system to an acceptable operating region. In this work, ±5% voltage variation is considered to be acceptable and hence, an immediate control action should be taken if power system is operated beyond this limit. The proposed method was tested on the IEEE 57-bus test system. Results showed that the proposed approach was able to provide a minimum amount of load shedding action to improve voltage profile of the studied power system.

***Keywords*—**voltage profile improvement, load shedding, linear programming, optimal power flow

I. Introduction

RECENT increase in power system loads has led such power system to operate near, even violate, its acceptable limits. In a short span of operating time horizon, an emergency action is commonly adopted to bring power system to a secure operating condition. One example of such emergency action is load shedding where a certain amount of load is required to be shed from the system to improve the overall performance of the power system.

In terms of time horizon, load shedding can be used to improve both transient (as an emergency action of a special protection system) and steady state security. As for power system variables, load shedding is usually carried out in the case of under frequency or under voltage occurs. Examples of utilizing load shedding for mitigating under frequency conditions are provided in [1], [2]. For mitigating under voltage problems, load shedding is utilized in [3]-[9]. Congestion management is also a class of problem to solve using load shedding. Such work was reported in [10].

In this work, voltage at all buses must be within the ±5% voltage variations from the nominal voltage. In order to achieve it, a minimum amount of load must be shed from the system if current loading condition results in under voltage situation. Therefore, a linear programming-based optimal power flow method is utilized to find the location where minimum load shedding can be carried out to bring bus voltage to be within the ±5% limits. This work extends our previous works as reported in [11], [12] by utilizing polar representation of the bus complex voltage. In [12], linear programming optimal power flow was applied to reactive power allocation problem while in this work, the method is modified to find optimum load shedding amount for voltage profile improvement. Moreover, to allow easier handling of voltage magnitude constraint, voltage is represented in polar coordinate using vector form which differs from rectangular representation in our previous works.

II. Problem Formulation

Mitigating voltage violation can be approached by actuating controls available in power system to bring it to its secure operating conditions. In this work, load shedding is an available control action. Therefore, final complex load at bus k after load shedding is:

$$S_k^{new} = S_k^{spec} - S_k^{shed} \tag{1}$$

The amount of load shedding per iteration may move towards both positive and negative directions. To accommodate this nature, load shedding variable is represented by two additional slack variables for both positive and negative directions during iteration process. Therefore total amount of load shedding at each bus of current iteration is updated by the following equation:

$$S_k^{shed} = S_k^{+} - S_k^{-} \tag{2}$$

Please note that in this work, load power factor remains constant as specified in the input data. In order to maintain power factor at bus k, relationship between active power and reactive power load held by the following relationship:

$$\rho_k = \tan\left(\cos^{-1}\left(P_k \Big/ \sqrt{P_k^2 + Q_k^2}\right)\right) \tag{3}$$

Due to additional slack variables of load shedding, complex power mismatch equation per iteration in equation (4) can be modified by accommodating equation (2) and results in equation (5):

$$\Delta S = S_{scheduled} - S_{calculated} \tag{4}$$

$$\Delta S - S_{load}^{+} + S_{load}^{-} = S_{gen} - S_{load}^{spec} - S_{calculated} \tag{5}$$

It is of important that the amount of load to be shed must be minimal and this can be achieved by using optimization method. Linear programming, due to its speed and robustness, is the preferable choice and incorporated into optimal power flow solution. Therefore, the linear objective function is minimization of overall load to be shed subject to operational power system constraints including the ±5% variations of nominal voltage at each bus. Equations (6) and (7) show the optimization model of load shedding minimization for voltage profile improvement. In this model, any changes in other variables, apart from the load shedding variables, have no cost associated to them.

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Objective function:

$$min. \sum_{k \in K} C_k^+ \cdot P_k^+ + C_k^- \cdot P_k^- \tag{6}$$

Subject to:

$$\begin{bmatrix} Real\left\{\frac{\partial \Delta S}{\partial V}\right\} & Real\left\{\frac{\partial \Delta S}{\partial \theta}\right\} & -1 & 1 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ Imag\left\{\frac{\partial \Delta S}{\partial V}\right\} & Imag\left\{\frac{\partial \Delta S}{\partial \theta}\right\} & 0 & 0 & -1 & 1 & -1 & 1 & 0 & 0 & -\rho & \rho \end{bmatrix} \cdot \begin{bmatrix} \Delta V_i \\ \Delta \theta_i \\ P_g^+ \\ P_g^- \\ Q_g^+ \\ Q_g^- \\ Q_s^+ \\ Q_s^- \\ P_k^+ \\ P_k^- \\ Q_k^+ \\ Q_k^- \end{bmatrix} = \begin{bmatrix} Real\{\Delta S_i\} \\ Imag\{\Delta S_i\} \end{bmatrix} \tag{7}$$

$i \in \mathbf{N}$; $g \in \mathbf{G}$; $s \in \mathbf{S}$; $k \in \mathbf{K}$

For all generators and loads, S = P ± jQ

Where:

- S is complex power injection at each bus in power system
- ΔS is mismatch of complex power injection S
- ΔV is voltage magnitude update variable at each bus
- $\Delta\theta$ is voltage angle update variable at each bus
- P_g^+ is active power generation update variable in positive axis
- P_g^- is active power generation update variable in negative axis
- Q_q^+ is reactive power generation update variable in positive axis
- Q_q^- is reactive power generation update variable in negative axis
- Q_s^+ is reactive power synchronous condenser update variable in positive axis
- Q_s^- is reactive power synchronous condenser update variable in negative axis
- P_k^+ is active power load shedding update variable in positive axis
- P_k^- is active power load shedding update variable in negative axis
- Q_k^+ is reactive power load shedding update variable in positive axis
- Q_k^- is reactive power load shedding update variable in negative axis
- ρ is trigonometric tangent of power angle
- C_k^+ is cost coefficient of active power load shedding update variable in positive axis
- C_k^- is cost coefficient of active power load shedding update variable in negative axis
- **N** is a set of all buses in power system
- **G** is a set of all generator buses in power system
- **S** is a set of all synchronous condenser buses in power system
- **K** is a set of all load buses in power system

In this model, all variables of voltages and powers are limited by their respective operational constraints.

Voltage is updated by the following equations:

$$V = V + \Delta V \tag{8}$$
$$\theta = \theta + \Delta\theta \tag{9}$$

III. Results and Discussions

The proposed method was applied to the IEEE 57-bus test system [13]. Single line diagram of this system as well as

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system data is available online in the public domain from [13]. By solving the base case, it was observed that this test system suffers from voltage violation of the acceptable ±5% variations. Base case scenario was conducted using standard Newton-Raphson power flow analysis.

As seen in figure 1, bus 31 experiences low voltage profile of below 95% limit in the base case scenario. Total load connected to this bus is 5.8 MW of active power and 2.9 MVAr of reactive power. In order to bring voltage magnitude at this bus to be within the acceptable limits, a certain amount of load must be shed. The same test system was then calculated using the proposed method to obtain how much load must be shed and at which bus. In this case, we assume that cost of performing this control action is similar at any bus, however; accommodating different cost coefficient to different bus for taking into account different contract scheme is trivial in the proposed formulation.

The proposed method suggested that 0.8025 MW and 0.4012 MVAr must be shed from Bus 31 in order to bring its voltage magnitude at 95% of the nominal voltage. Voltage profile of the IEEE 57-bus system after load shedding is shown in figure 2.

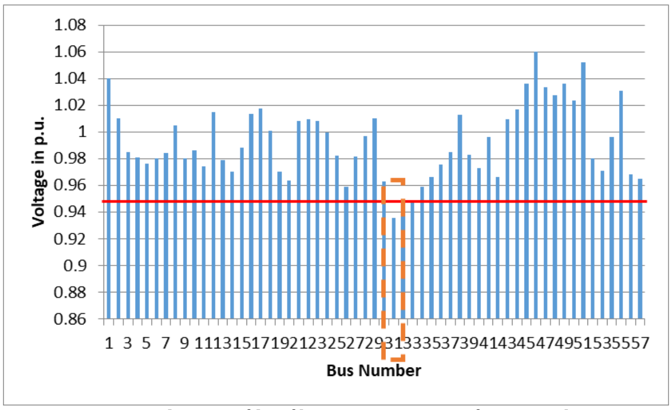

Fig. 1. Voltage profile of base case scenario of IEEE 57-bus

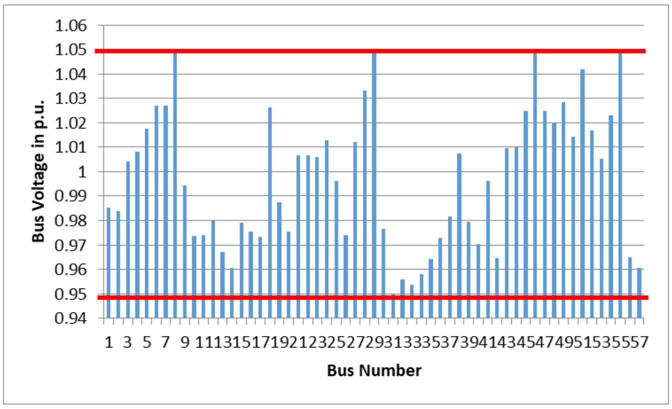

Fig. 2. Voltage profile of IEEE 57-bus after load shedding

The next test for the developed method is solving low voltage profile problem in many buses. In this case, the IEEE 57-bus is modified such that it is loaded 1.3 times of the original loading condition. This is achieved by multiplying all initial loads with a scalar value of 1.3. This increase of loading condition results in almost one-third of total buses suffers from voltage magnitude of lower than 95% limit. Voltage profile of this situation is indicated in figure 3.

In order to tackle this poor voltage profile in figure 3, the developed method suggested a total of 11.61 MW load to be shed. Due to very low voltage magnitude at Bus 31, i.e. 84% of the nominal voltage, a large amount of load is required to be shed, i.e. 5.24 MW. Table 1 shows the amount of load shedding required to improve voltage profile of the modified case of the IEEE 57-bus. An improved voltage profile is shown in figure 4.

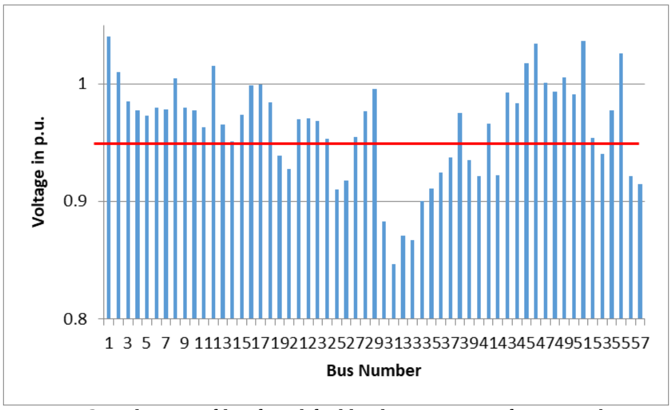

Fig. 3. Voltage profile of modified loading scenario of IEEE 57-bus

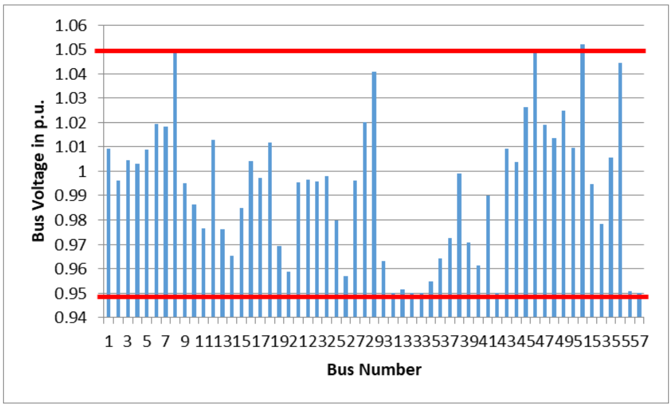

Fig. 4. Voltage profile of modified loading scenario of IEEE 57-bus after load shedding

TABLE 1. LOCATION AND AMOUNT OF LOAD SHEDDING REQUIRED

Bus #	Active Power Load Shedding	Reactive Power Load Shedding
31	5.24 MW	2.62 MVAr
33	2.39 MW	1.19 MVAr
42	0.25 MW	0.16 MVAr
57	3.73 MW	1.11 MVAr

IV. Conclusions

System suffers from low voltage magnitude profile or experiences under voltage condition, requires an emergency action to bring such system to an acceptable operating region. In this work, load shedding is proposed as the control action and the amount load to be shed is calculated by means of linear programming-based optimal power flow. Two cases were considered in this work, i.e. single bus and several buses experience under voltage. Results show that the developed approach is able to provide minimum amount of load shedding to bring the voltage to acceptable limits. Future work will include more control variables to the formulation and application of the developed approach to smart grid may be further examined.

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