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A New Approach for Corrective and Preventive Control to Unsolvable Case in Power Networks having DERs

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Abstract – Recently, Korean system operating conditions have gradually approached an upper limit. When a contingency occurs, the power system may have no solutions. Different from the cases of bad initial guesses or the solutions are too close to the solvability boundary in which numerical methods can be applied, for unsolvable cases, the only way to restore solvability would be structure modifications. In this paper, a new approach for corrective and preventive control to such cases is proposed in two steps: (i) finding any solution regardless its feasibility; (ii) for the infeasible solution, make it feasible with additional modifications at load buses having Distributed Energy Resources. The test case built based on the peak load profile of 2008 by KEPCO including 1336 buses is analyzed. Since reactive power compensation is optimized to restore solvability, all demands are met, therefore no blackouts happen. The proposed method was integrated in the LP program designed by power21 Corporation.

Keywords: Convergence, DERs, Newton-Raphson method, Power flow, PTDFs, Solvability.

1. Introduction

In recent times, Korean power system operating conditions have gradually approached an upper limit. When a contingency occurs, the power system may have unsolvable cases for which power flow solutions do not exist [1]. Power flow divergence problem can transpire for three main causes: bad initial guess, the solution is too close to the unsolvable boundary or the systems actually have no solutions. For the two former causes, numerical methods such as optimal multiplier [2] or continuation power flow [3] can be applied. However, for the last case, the only way to restore solvability would be structure modifications. A significant number of researchers have proposed various methods to deal with this problem [4-10]. These works, in fact, have their own advantages, limitations and disadvantages. In 1994-1995, Overbye presented a method for determining system controls in order to restore the power flow based on a damped Newton-Raphson (N-R) power flow algorithm and a sensitivity analysis [4-5]. This method is able to find out the minimum of the cost function (the closest point on the solvable boundary) and the best direction to shed the loads to restore solvability. Nevertheless, the solution depends on the curvature of the solvable boundary and the errors are minor if the boundary is flat. Another limitation is lack of interaction between voltage control actions. The disadvantage is using load shedding to restore solvability. In 1996, Granville et al. adopted the direct interior point method in an optimal power flow in order to calculate the minimum load shedding to restore the power flow [6]. This method had some advantages like ability to take in account all constraints, combination reactive power control and minimizing load shedding, and overcoming problem of Jacobian matrix singularity with conventional power flow. Howbeit, it consumed time and required a great computational effort due to its complexity and difficulty of dividing the networks. In 1998, Feng et al. described a method for determining the minimum load shedding required to find the equilibrium point associated with the post-contingency boundary [7]. Feng's method could minimize the control actions and identify the most effective control strategy but this also consumes time and the loads must be curtailed. In 2000, Luciano V. Barboza modeled the problem of restoring the solvability of the power flow equations as the minimization of the summation of the squares of the power flow mismatches subject to equality constraints [8]. This method combined simplicity of the steady state network equations and the efficiency of Newton method and required less computational effort. Luciano V. Barboza followed the idea of loads shedding thereby the system partly experienced blackouts. Solvability restoration with reactive power compensation was mentioned in [9] Andre G.C. Conceicao proposed a method included two steps: (i) quantifying the systems unsolvability degree (UD); (ii) determining a corrective control strategy to pull system back to feasible region. This work took in account various voltage controls but it ignores the locally effect of voltage control like switch shunts (SS) controls, only considers the changing of reactive power at the bus where SS resides. Moreover, it took time to search the controls in the network. Finally, in 2011, Sangsoo Seo et al. introduced

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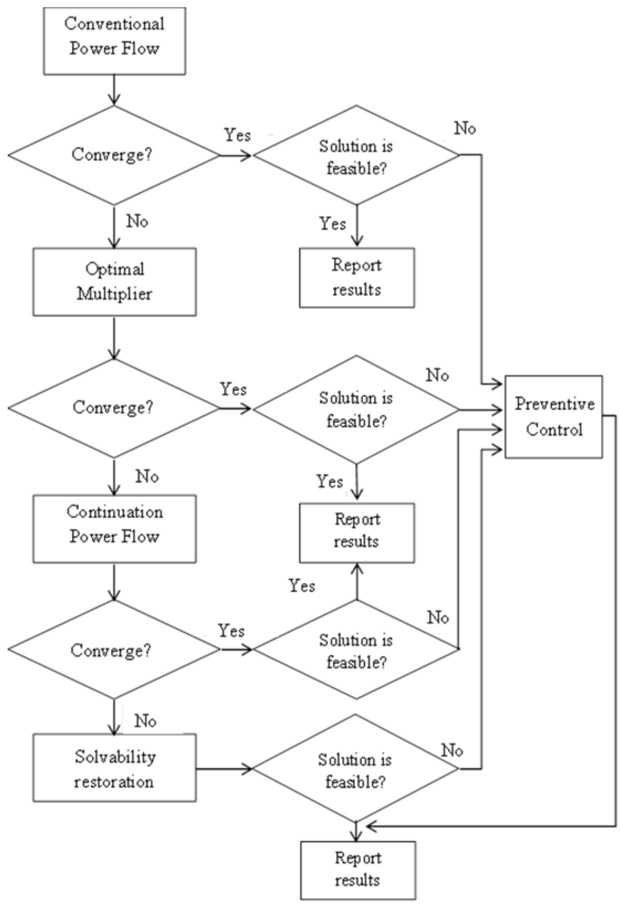
a methodology using a tool based on the branch-parameter continuation power flow (BCPF) in order to restore the power flow solvability in unsolvable contingencies [1]. This method is able to maintain loads by compensate reactive power. Similar to previous works, it lacks for capturing the locally effect of voltage control. The main drawbacks are that it much depends upon the network configuration and consumes time to search the lines for shipping.

The method of shedding load, indeed, has some appropriateness such as effective implementation in a large scale, ability to find the "optimal" direction to curtail the load and there are small errors in estimation [5, 9]. However, by using load shedding for restoration, the system must experience blackouts. Moreover, large errors in estimation can be lessened by applying a better linearizing method which is able to capture high non-linear factors. This paper outlines a framework for determining the necessary reactive power compensation, instead of load shedding, to restore the power system. Divergence occurs when solving the load flow equations is assumed only related to reactive power problem, therefore only reactive power modifications have been carried out. This methodology uses linearizing techniques and least square minimization to reduce power flow mismatch by controlling switched shunts. As a result, the feasible boundary is enlarged to cover the operation point and power flow problem is solved. The strategy is implemented in two steps: (i) finding any solution regardless its feasibility (Corrective control); (ii) for the infeasible solution, make it feasible with additional modifications to voltage at load buses having Distributed Energy Resources (DERs) (Preventive control). A detail description is given in the following flow chart. The proposed method has been being integrated in the load flow program designed by power 21 Corporation.

2. Corrective Control

For the case of divergence, mismatch of N-R method tends to increase over iterations, so the computation loop never terminates. Overbye pointed out that the system can be moved back to the solvable region boundary if the power injections are changed so all bus mismatches are set to zero [4]. The proposed idea is to tackle the problem of divergence by finding ways to reduce this mismatch. However, instead of changing power injections, if we can compensate reactive power such that minimizing the mismatch, power flow will converge or the operation point will be in solvable region. Furthermore, appropriate reactive power compensation will support the voltage profile then the lower limit of voltages increases which ensures the solution exists [10-11]. In this section, the concepts of Sphere of Influence (SOI) and Power Transfer Distribution Factors (PTDFs) are introduced. SOI then is utilized to localize voltage control effect of a voltage controlled bus. Besides, PTDFs are useful for linearizing the network which can be used to derive some simple relationships between deviations of reactive powers and voltages.



Flow chart: The Corrective – Preventive control algorithm

2.1 PTDFs

The reactive power flows through the line l_{ij} between bus i and bus j can be computed as:

$$Q_{l(ij)} = -V_i^2 \cdot B_{ij} - V_i \cdot V_j \cdot [G_{ij} \cdot \sin(\delta_i - \delta_j) - B_{ij} \cdot \cos(\delta_i - \delta_j)] \quad (1)$$

where V_i , δ_i and V_j , δ_j are the voltage magnitudes and angles of bus i and bus j, respectively; G_{ij} and B_{ij} is the conductance and the susceptance of line l_{ij} , respectively. Since transmission links are mostly reactive, the conductance G_{ij} is quite small then the term involving G_{ij} is also quite small. This is still valid when applying to the derivative of $Q_{l(ij)}$. Normally, the angle $\delta_i - \delta_j$ is reasonably small therefore its sine term can be omitted in (1). The same reasoning is used in so-called decoupled power flow which simplifies the N-R algorithm for solving the power flow Eqs. [25]. If G_{ij} and ($\delta_i - \delta_j$) can be neglected, the above formula becomes:

$$Q_{l(ij)} \approx -B_l (V_i^2 - V_i V_j \cos\delta_{ij}) \quad (2)$$

Now PTDF of the reactive power through the line l_{ij} with respect to the reactive power of load bus k is obtained as:

$$\begin{aligned} p_{ij-k} &= \frac{dQ_{l(ij)}}{dQ_k} \\ &= -B_{ij} \cdot \frac{d}{dQ_k}(V_i^2 - V_i V_j \cos\delta_{ij}) \\ &= -B_{ij}.V_i \frac{2}{\frac{\partial Q_k}{\partial V_i}} + B_{ij}(V_j \cos\delta_{ij} \frac{1}{\frac{\partial Q_k}{\partial V_i}} + V_i \cos\delta_{ij} \frac{1}{\frac{\partial Q_k}{\partial V_j}} \\ &\quad - V_i V_j \sin\delta_{ij} (\frac{1}{\frac{\partial Q_k}{\partial \delta_i}} - \frac{1}{\frac{\partial Q_k}{\partial \delta_j}})) \quad (3) \\ &= -B_{ij}.(2V_i - V_j \cos\delta_{ij}) \frac{1}{\frac{\partial Q_k}{\partial V_i}} + B_{ij} V_i (\frac{\cos\delta_{ij}}{\frac{\partial Q_k}{\partial V_j}} \\ &\quad - V_j \sin\delta_{ij} (\frac{1}{\frac{\partial Q_k}{\partial \delta_i}} - \frac{1}{\frac{\partial Q_k}{\partial \delta_j}})) \end{aligned}$$

where Q_k is the reactive power of load bus k .

2.2 Sphere of Influence

The tier approach is an efficacious structure organization of the electric power system network used for simplifying the computation process with minor errors. As shown in Fig. 1, the considered bus where a switched shunt (SS) resides is defined as the center bus. All load buses directly link to the centric bus are in the first tier. Subsequent tiers include load buses which are directly link to the load buses in previous tier. Since SS control affects the network only locally [17-18], there exists a positive integer N such as

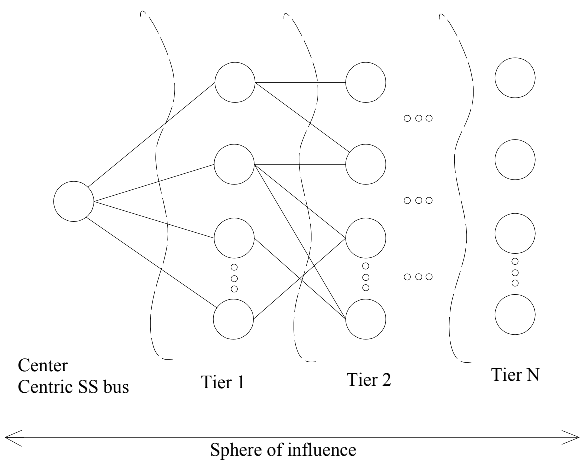


Fig. 1. The sphere of influence

voltages of load buses in tier N+1 are not affected by the centric bus control. Therefore, tier N is the fringe one. SOI of the centric bus is defined as the subset includes all load buses participate in from the first tier to the fringe. Voltages at others buses which do not belong to SOI will be fixed when centric bus controls voltage.

Electrical Distance based method developed by Electricite de France (EDF) [19] is useful for quantifying the fringe. The different physical variables of a meshed electrical system are linked by the matrix equations presented below:

$$[\Delta I] = [Y_{bus}][\Delta V] \qquad [\Delta Q] = [\partial Q / \partial V][\Delta V]$$
$$[\Delta V] = [Z_{bus}][\Delta I] \qquad [\Delta V] = [\partial V / \partial Q][\Delta Q]$$

The matrix $[Y_{bus}]$ is the matrix of admittances. The matrix $[Z_{bus}]$ is the matrix of impedances. Both matrices are the inverse of each other, complex and symmetrical. The matrix $[\partial Q / \partial V]$ is part of the Jacobian matrix which appears during a load-flow computation following the N-R method. Its inverse $[\partial V / \partial Q]$ is called sensitivity matrix. A matrix of attenuations between all the nodes of system, whose terms are written a_{ij} , is then available. We have:

$$\Delta V_i = \alpha_{ij} \Delta V_j \text{, with } \alpha_{ij} = \left[\frac{\partial V_i}{\partial Q_j}\right] / \left[\frac{\partial V_j}{\partial Q_j}\right] \approx \frac{B_{jj}}{B_{ij}}$$

To obtain symmetrical distances, the formulation below is taken as definition of the electrical distance between two nodes i and j: $D_{ij} = D_{ji} = -Log(\alpha_{ij} \ . \ \alpha_{ji})$

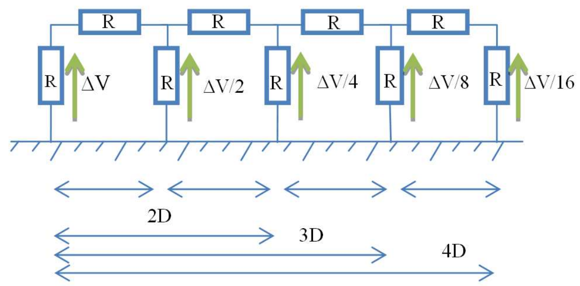


Fig. 2. The attenuations on a simple example

The electrical distances once specified can be used to determine the zones and pilot nodes of the secondary (regional) voltage control which is widely accepted and has been implemented in some European systems, for example in France [20] and Italy [21]. As a matter of fact, attenuation factors computed by EDF do not reflect well the systems under heavy load conditions [22]. The following method is developed to overcome these situations.

In this paper, attenuation factors based PTDFs are proposed. The desired result the attenuation factor α satisfies:

$$\Delta V_i = \alpha_{ij} \Delta V_j \quad (1)$$

where ΔV_i and ΔV_j are the variation of voltage at bus i and bus j, respectively. The detail description is in the Preventive Control session.

2.3 Linearizing the network

If the switched shunt resides at bus i (center), we define Ω_1, Ω_N as:

$$\Omega_1 = \Omega(T1) = \{j \mid \text{bus } j \in \text{tier } 1\};\ \aleph(\Omega_1) = n_1$$
$$\Omega_N = \Omega(SOI) = \{k \mid \text{bus } k \in \text{SOI}\};\ \aleph(\Omega_N) = n_N$$

where $\aleph(\cdot)$ is the cardinality of a set. Obviously, Ω_1 belongs to Ω_N. Then the table of p_{ij} is constructed as:

Table 1. Power Transfer Distributed Factors

Load \ Line	ij	i(j+1)	...
k	$p_{ij\text{-}k}$	$p_{i(j+1)\text{-}k}$	...
k+1	$p_{ij\text{-}(k+1)}$	$p_{i(j+1)\text{-}(k+1)}$	...
...	...	...	...

where $j \in \Omega_1$; $k \in \Omega_N$; cells in Table 1 represent the PTDF of the reactive power through the lines with respect to the reactive power of load buses, for instant the entry of $p_{ij\text{-}k}$ represents the PTDF of the reactive power through the line l_{ij} and load bus k.

The reactive power deviation of each line can be computed as:

$$\Delta Q_{l(ij)} = \sum_{k \in \Omega_N} \frac{dQ_{l(ij)}}{dQ_k} \Delta Q_k ;\ j \in \Omega_1 \tag{13}$$

Let $p_{ij-k} = \dfrac{dQ_{l(ij)}}{dQ_k}$ then

$$\Delta Q_{l(ij)} = \sum_{k \in \Omega_N} p_{ij-k} \Delta Q_k ;\ j \in \Omega_1 \tag{14}$$

where $\Delta Q_{l(ij)}$ and ΔQ_k are the reactive power deviation of line l_{ij} and the load at bus k. The mismatch of reactive power at bus i where switched shunt (SS) resides can be represented in terms of lines reactive power deviation:

$$\Delta Q_i = \sum_{j \in \Omega_1} \Delta Q_{l(ij)} \tag{15}$$

In matrix form it becomes:

$$\Delta Q_i = \left[p^i\right]\left[\Delta \underline{Q}_k\right] \tag{16}$$

Where

$$\left[p^i\right] = [p^i_j \ldots p^i_k \ldots p^i_{j+n_N-1}] \in R^{1 \times n_N}$$

$$p^i_k = \sum_{j \in \Omega_1} p_{ij-k} ;\ k \in \Omega_N$$

$$\left[\Delta \underline{Q}_k\right] = [\Delta Q_j \ldots \Delta Q_k \ldots \Delta Q_{j+n_N-1}]^T \in R^{n_N \times 1}$$

Or in another way:

$$\Delta Q_i = \left[\mathbf{0}\, p^i_j \ldots p^i_k \ldots p^i_{j+n_N-1}\right] \begin{bmatrix} \Delta Q_i \\ \Delta Q_j \\ \ldots \\ \Delta Q_{j+n_N-1} \end{bmatrix} \tag{17}$$

Similarly, these following expressions are derived:

$$\Delta Q_j = \left[p^j_i\, \mathbf{0} \ldots p^j_k \ldots p^j_{j+n_N-1}\right] \begin{bmatrix} \Delta Q_i \\ \Delta Q_j \\ \ldots \\ \Delta Q_{j+n_N-1} \end{bmatrix} \tag{18}$$

$$\Delta Q_{j+n_N-1} = \left[p^{j+n_N-1}_i\ p^{j+n_N-1}_j \ldots p^{j+n_N-1}_k \ldots \mathbf{0}\right] \begin{bmatrix} \Delta Q_i \\ \Delta Q_j \\ \ldots \\ \Delta Q_{j+n_N-1} \end{bmatrix}$$

Solving the set of n_N above equations we get:

$$-\begin{bmatrix} p^j_i \\ \ldots \\ p^k_i \\ \ldots \\ p^{j+n_N-1}_i \end{bmatrix} * \Delta Q_i = \begin{bmatrix} -\mathbf{1} & \ldots & p^i_k & \ldots p^i_{j+n_N-1} \\ \ldots & \ldots & \ldots & \ldots \\ p^k_j & \ldots & -\mathbf{1} & \ldots p^k_{j+n_N-1} \\ \ldots & \ldots & \ldots & \ldots \\ p^{j+n_N-1}_j & \ldots p^{j+n_N-1}_k & \ldots & -\mathbf{1} \end{bmatrix} \begin{bmatrix} \Delta Q_j \\ \ldots \\ \Delta Q_k \\ \ldots \\ \Delta Q_{j+n_N-1} \end{bmatrix} \tag{19}$$

Or

$$-N * \Delta Q_i = M * \begin{bmatrix} \Delta Q_j \\ \ldots \\ \Delta Q_k \\ \ldots \\ \Delta Q_{j+ni-1} \end{bmatrix} \tag{20}$$

Then

$$\begin{bmatrix} \Delta Q_j \\ \ldots \\ \Delta Q_k \\ \ldots \\ \Delta Q_{j+ni-1} \end{bmatrix} = -M^{-1} N * \Delta Q_i \tag{21}$$

where $-M^{-1}N$ is of the form:

$$-M^{-1}N = U = [u]_{ni\ x\ 1} = \begin{bmatrix} u_j \\ \dots \\ u_k \\ \dots \\ u_{j+ni-1} \end{bmatrix} \quad (22)$$

From (14), (21) and (22), we have:

$$\Delta Q_{l(ij)} = \sum_{j\in\Omega_1, k\in\Omega_N} p_{ij-k} u_k \Delta Q_i = \Delta Q_i \sum_{k\in\Omega_N} p_{ij-k} u_k = h_{ki}\Delta Q_i ; j \in \Omega_1 \quad (23)$$

where $h_{ij-i} = \sum_{k\in\Omega_N} p_{ij-k} u_k ; j \in \Omega_1$

Let ΔQ_{ss-i} be amount of reactive power change due to SS at bus i then the reactive power transferred from bus i to bus j will vary with amount of ΔQ_{ss-ij} and

$$\Delta Q_{ss-i} = \Delta Q_i$$

$$\Delta Q_{ss-ij} = \Delta Q_{l(ij)}$$

Then $$\Delta Q_{ss-ij} = h_{ij-i}\Delta Q_{ss-i} \quad (24)$$

Equation (24) shows that how the reactive power transferred from bus i to bus j varies when SS changes.

Least square minimization

Based on the above tier approach, it is able to divide the network into several Zones according to the group of local switched shunts. Let $[\Delta Q]$ be mismatch vector we derive after some iterations. There are 4 steps to divide the network:

Step 1: Forming Zone 1

- Search the network to find the bus with largest mismatch. The mismatch vector is provided after each N-R iteration.
- The closest SS bus to the largest mismatch bus will be chosen as the centric bus.
- Find the SOI for this center and all load buses in this SOI will be added to Zone 1.

Step 2: Expanding Zone 1

- Each SS bus in Zone 1, in turn, is set as center
- Find SOIs for these centers
- All buses belong to these SOIs will be added to Zone 1.

Step 3: Continue expanding Zone 1 until:

- There are no more SS buses in Zone 1 to set as centric bus or
- The number of buses in Zone 1 is more than the limited size of full matrix is able to solve. The reason is that the matrix of $[-H]^T[-H]$ in (30) is a full one hence it is difficulty to invert. In fact, there is a limitation of full matrix size with a certain computer. The limitation depends on the computer configuration and the solver as well.

Step 4:

- Forming Zone 2, Zone 3 with the rest buses until all SS buses are listed in Zones.

For each Zone, its switched shunts are controlled to reduced mismatch of buses inside. For some Zone with n buses and m SS buses with m < n, the mismatch is:

$$[\Delta \underline{Q}] = \begin{bmatrix} \Delta Q_i \\ \dots \\ \Delta Q_j \\ \dots \\ \Delta Q_{i+n-1} \end{bmatrix} \quad (25)$$

After SS changes, the new mismatch vector is:

$$[\Delta \underline{Q}'] = \begin{bmatrix} \Delta Q'_i \\ \dots \\ \Delta Q'_j \\ \dots \\ \Delta Q'_{i+n-1} \end{bmatrix} \quad (26)$$

From (15): $\Delta Q_{ss-ij} = h_{ij-i}\Delta Q_{ss-i}$ where $h_{ij-i} = 0$ if $B_{ij} = 0$. Then

$$\begin{bmatrix} \Delta Q'_i \\ \dots \\ \Delta Q'_j \\ \dots \\ \Delta Q'_{i+n-1} \end{bmatrix} = \begin{bmatrix} \Delta Q_i \\ \dots \\ \Delta Q_j \\ \dots \\ \Delta Q_{i+n-1} \end{bmatrix} + \begin{bmatrix} h_{ii} \\ \dots \\ h_{ji} \\ \dots \\ h_{(i+n-1)i} \end{bmatrix} \Delta Q_{ss-i} + \begin{bmatrix} h_{ij} \\ \dots \\ h_{jj} \\ \dots \\ h_{(i+n-1)j} \end{bmatrix} \Delta Q_{ss-j} + \dots \quad (27)$$

where $h_{ii} = \sum_k h_{ik-i}$; $h_{ji} = \sum_k h_{jk-i}$; $h_{(i+n-1)i} = \sum_k h_{(i+n-1)k-i}$; bus i, j,… are SS buses.

Eq. (27) is rewritten as:

$$\begin{bmatrix} \Delta Q'_i \\ \dots \\ \Delta Q'_j \\ \dots \\ \Delta Q'_{i+n-1} \end{bmatrix}_{nx1} = \begin{bmatrix} \Delta Q_i \\ \dots \\ \Delta Q_j \\ \dots \\ \Delta Q_{i+n-1} \end{bmatrix}_{nx1} + \begin{bmatrix} h_{ii} & \dots & h_{ij} & \dots \\ \dots & \dots & \dots & \dots \\ h_{ji} & \dots & h_{jj} & \dots \\ \dots & \dots & \dots & \dots \\ h_{(i+n-1)i} & \dots & h_{(i+n-1)j} & \dots \end{bmatrix}_{nxm}$$

$$\begin{bmatrix} \Delta ssQ_i \\ \dots \\ \Delta ssQ_j \\ \dots \end{bmatrix}_{mx1} \quad (28)$$

Or:

$$\Delta^{'} = \Delta + H\Delta ss \quad (29)$$

And we try to minimize $\|\Delta'\|_2$ with respect to the change of SS buses (Δss). To minimizing mismatch $\Delta^{'}$ is a standard Least Square Minimization and the solution is

$$\Delta ss = \left([-H]^T[-H]\right)^{-1}[-H]^T\Delta \quad (30)$$

Based on Δss, SS is controlled to minimize mismatch in the considered Zone. Simply, a negative Δ entry indicates the shortage of reactive power then SS will be controlled to compensate reactive power there. An excess of reactive power is denoted by a positive Δ entry and control actions need to withdraw reactive power.

The proposed method has various advantages such as optimizing reactive power compensation, ability to tackle with a large and complex system, maintaining all the demands thereby no blackouts occur, fast and less computational burden. However, there are some existing limitations because this method does not take in account limitations of reactive sources and diversity of voltage control types. It only deals with load flow divergent problem pertaining to reactive power. Moreover, the main disadvantage of the method is that it is difficult to find the "best" iteration to apply the proposed method, therefore it is needed to trade-off between accuracy, time consuming and ability to restoring solvability.

3. Preventive Control

3.1 Method for steady state voltage monitoring and control [17]

[17] describes the theoretical and algorithmic enhancements of the method for steady state voltage monitoring and control. The approach in the proposed method is to attempt to maintain a given "optimal" voltage profile as the load demand, generation availability and network topology vary. In mathematical terms, the problem is to minimize $\|\Delta V_L\|_2$, a vector of load voltage deviation only.

3.2 The attenuation factor α based on PTDFs

The desired result the attenuation factor α satisfies:

$$\Delta V_{DER} = \alpha \Delta V_L \quad (31)$$

where ΔV_{DER} and ΔV_L are the variation of voltage at terminal of DER and at the load bus needed to control voltage. From (12) and (13), we have:

$$\begin{bmatrix} \Delta Q_j \\ \dots \\ \Delta Q_k \\ \dots \\ \Delta Q_{j+ni-1} \end{bmatrix} = U * \Delta Q_i \quad (32)$$

By introducing the DER reactive power mismatch $\Delta Q_{DER} = \Delta Q_i$, (32) is rewritten as:

$$\begin{bmatrix} \Delta Q_{DER} \\ \Delta Q_j \\ \dots \\ \Delta Q_k \\ \dots \\ \Delta Q_{j+ni-1} \end{bmatrix} = \begin{bmatrix} \mathbf{1} \\ U \end{bmatrix} * \Delta Q_{DER} \quad (33)$$

The power flow equations can be rewritten as:

$$[J_V]\begin{bmatrix} \Delta V_{DER} \\ \Delta V_j \\ \dots \\ \Delta V_k \\ \dots \\ \Delta V_{j+ni-1} \end{bmatrix} = \begin{bmatrix} \Delta Q_{DER} \\ \Delta Q_j \\ \dots \\ \Delta Q_k \\ \dots \\ \Delta Q_{j+ni-1} \end{bmatrix} \quad (34)$$

Where $[J_V]$ is a part of Jacobian matrix corresponding the deviation of voltage and mismatch of reactive power at DER bus and related buses listed in (27). Combining (33) and (34), we derive:

$$[J_V]\begin{bmatrix} \Delta V_{DER} \\ \Delta V_j \\ \dots \\ \Delta V_k \\ \dots \\ \Delta V_{j+ni-1} \end{bmatrix} = \begin{bmatrix} \mathbf{1} \\ U \end{bmatrix} * \Delta Q_{DER} \quad (35)$$

Then

$$\begin{bmatrix} \Delta V_{DER} \\ \Delta V_j \\ \cdots \\ \Delta V_k \\ \cdots \\ \Delta V_{j+ni-1} \end{bmatrix} = \left[J_V\right]^{-1}\begin{bmatrix} \mathbf{1} \\ U \end{bmatrix} * \Delta Q_{DER} \qquad (36)$$

Let

$$\left[J_V\right]^{-1}\begin{bmatrix} \mathbf{1} \\ U \end{bmatrix} = D = \begin{bmatrix} d_{DER} \\ d_j \\ \cdots \\ d_k \\ \cdots \\ d_{j+ni-1} \end{bmatrix} \qquad (37)$$

Assume that bus j is the bus with low voltage, i. e $V_j < \mathbf{0.95}$. We need to raise its voltage equals 0.95. To do that, the DER will increase the terminal voltage as:

$$\Delta V_{DER} = \frac{d_{DER}}{d_j}(\mathbf{0.95} - V_j) = \alpha \Delta V_j \qquad (38)$$

$$\alpha = \frac{d_{DER}}{d_j} \qquad (39)$$

Obviously, the value of α can be used to quantify the electrical distances as mentioned in the part of 2.2.2. Since the PTDFs computation takes in account the high non-linear components, this approach gives more precise results compared to one developed by EDF.

Since DERs control reactive power outputs if DERs are based on inverters, it is reasonable to derive the equation for ΔQ_{DER} and ΔV_j. From (36) and (37), we have:

$$\Delta V_j = d_j . \Delta Q_{DER} \qquad (40)$$

then $$\Delta Q_{DER} = \frac{\mathbf{1}}{d_j}\Delta V_j = \beta_j . \Delta V_j \qquad (41)$$

where $$\beta_j = \frac{\mathbf{1}}{d_j} \qquad (42)$$

Preventive control is a promising method for steady state voltage control because of its simplicity and good approximations which turn out precise results. Nevertheless, it is still limited due to lack of voltage control coordination and requiring DERs ubiquity. As a matter of fact, the proposed method much depends on voltage control ability of DERs.

4. Case Study

4.1 Solvability restoration: Korean case

In this section, a test case is presented: this test case built based on the peak load profile of 2008 in Korea by Korea Electric Power Corporation (KEPCO). This test case includes 1336 buses with 1247 load buses and 338 switched shunts buses.

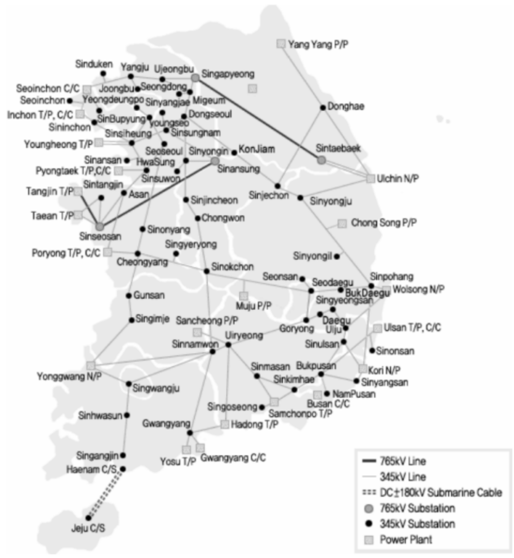


Fig. 3. Transmission diagram of the Korean power system

Due to high reactive demands and inappropriate allocation of switched shunts, the system has no solutions as a result power flow solved by N-R method diverges.

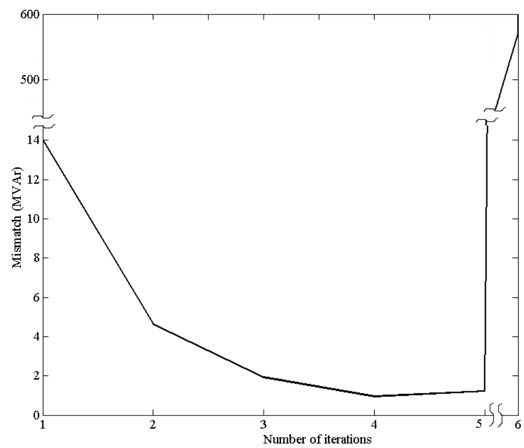


Fig. 4. Convergence characteristic of original problem

After the first six iterations, mismatch dramatically increases to $\mathbf{10^7}$ MVAR, and power flow starts to diverge. The proposed method showed a good performance dealing with the divergence problem.

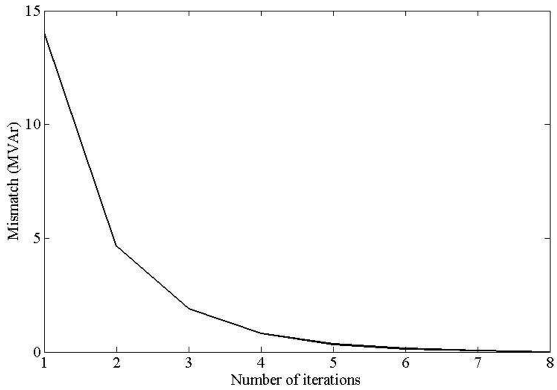


Fig.5. Convergence characteristic of PF with controlled SS

By applying the new method, mismatch obviously decreases and finally, power flow converges.

4.2. Preventive control

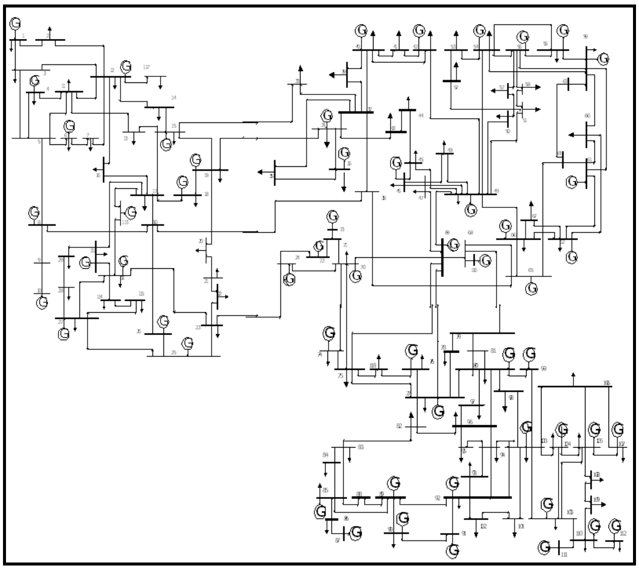


Fig. 6. The IEEE 118-bus test case

Preventive control has been tested for the IEEE 118-bus system to demonstrate its effect. In which, load bus #118 has a low voltage of 0.94741 and the DER resides at bus #76. The target of the program is controlling the terminal voltage of the DER to raise the voltage at bus #118 to $V_{desired} = \mathbf{0.95}$ based on information of the factor α .

With $\alpha_{118} = \mathbf{0.5790}$, $\Delta V_{118} = \mathbf{0.00259}$ the DER must be set a new terminal voltage:

$$V'_{DER} = V_{DER} + \alpha_{118}.\Delta V_{118} = \mathbf{0.9582}$$

From the results shown in Table 2, the new voltage at DER bus #76 is 0.9582 and the voltage at the load bus #118 is improved and equals to $V_{desired} = \mathbf{0.95}$.

Table 2. Results of Power Flow with DER Control

BUS#	NAME	VOLT		ANGLE	ALPHA
		Before control	After control		
38	BUS-38	0.96188	0.96189	17.1	0.001
45	BUS-45	0.98675	0.98676	15.8	0.001
75	BUS-75	0.96753	0.96790	22.9	0.0758
76	BUS-76	0.9520	0.9582	21.8	1
118	BUS-118	0.94741	0.9503	21.9	0.5790

5. Conclusion

The proposed method is proved to be very powerful, flexible and able to deal with the problem of divergence in a large and high non-linear system. Since $[-H]^T[-H]$ is a full matrix, it is difficult to handle with large size. Therefore, Zones must be chosen in order to ensure ability to solve and achieve a good approximation.

Since the proposed method does not take in account the constraints of reactive power compensation, in order to improve the program and apply in the real-life, it is necessary to examines how the limits affect the method's performance. The idea of control based on the sensitivities of mismatch with respect to vector control u [5, 7] can be combined with the proposed method to find a better control strategy.

Based on this program, a new feasible boundary which pertains to the system correcting ability can be found. This information is meaningful for the system operators, in a sense they have a good feel of the current system.

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