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Simple Reformation of Conventional Power Flows to Enhance Resilient Power Grid Analysis

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SUMMARY

This paper presents a robust distributed slack bus method to improve the conventional power flow applications in Energy Management System (EMS) for a resilient power grid. The paper introduces the impact of renewable generation resources. It describes how the proposed approach uses participation factors to allocate generation on a single slack bus in the conventional methods into all online generators in a power system. Various types of generation resources can be involved in the optimal re-dispatch process through their participation factors, including renewable, fossil or any regulated and deregulated resources of a mixed power system. The test results obtained from a modified IEEE-30 bus system highlight the advantages of the distributed slack bus approach. The proposed approach can reduce line losses, improve bus voltage profiles and optimize generation dispatch. This method can be simply implemented in conventional power flow algorithms of existing EMS and promises to enhance resilient power grid analysis.

KEYWORDS

Power Flows, Power System Modeling, Power System Operations, and Resilient Power Grid

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I. INTRODUCTION

As renewable energy wind farms and solar fields significantly increase in power grids, the generation pattern has been gradually shifting from combined conventional fossil resources (such as coal and natural gas). Nuclear, oil and a very small portion of hydropower have given way to continually-increasing portions of renewable energy (including wind, solar and energy storage devices). Power system operations and analyses must be prepared to face these new challenges. In power flow analysis and power system network modeling, various types of generators and their corresponding characteristics should simultaneously be adapted for this change.

Regional Transmission Organizations/Independent System Operators (RTO/ISO) and grid operators have faced challenges in their existing EMS, related to evolving power flow solution methods in this new operational environment. Concepts and knowledge of distributed slack bus use have been applied for competitive electricity market studies during the past two decades. Successful examples include the Locational Marginal Pricing (LMP) calculations using distributed slack bus in [1-2]. The distributed slack bus application helps with the comparability of generation offers and load bids in a deregulated power market. In a series of recently published papers, the distributed slack bus idea has been widely applied to various modern power systems, such as smart grids in [3], renewable energy, distributed generators (DG) [4-5] and optimal power system control [6]. Research papers [7] and [8] outline the distributed slack bus applications in traditional Newton-Raphson (N-R) and fast decoupled power flow solution methods. The modified N-R method [7] considered only distributing system loss, and the method [8] utilized graph computing based solutions with multiple slack buses in fast decoupled power flow. Some commercial EMS vendors have claimed to add the distributed slack bus concept into their newest versions of EMS and power flow study tools, but there are limitations in power flow balances, voltage regulating control, and contingency analysis. Differing from the vendor approach, this paper concentrates on a simple reformation of conventional power flow methods by utilizing a distributed slack bus concept for the resilient power system. It provides a new power flow algorithm based on conventional N-R power flow and fast decoupled load flow solution methods to enhance existing EMS tools serving power system operation. These reformed load flow algorithms easily contain the characteristics of new types of energy resource in power system operation and analysis.

This paper briefly recalls fundamental power flow methods in Section II. It derives the participation factors for all generators in a power system in Section III, where each generator takes on the system power supply based on their respective participation factors. Section IV explores how to embed participation factors into the conventional N-R power flow and decoupled load flow methods. The new proposed formulation is tested with the modified IEEE 30 bus system in Section V. The solution proves the effectiveness of the proposed power flow approach, adopts realistic roles of various power resources and makes up for the lack of power flows in existing EMS. The test results demonstrate the practical value of this proposed algorithm. This approach is quite effective for power system engineers and system operators in analyzing the system situation, evaluating the impact of wind and solar power contributions, in developing short-term operation strategies and ensuring the reliability of power system operations.

II. REVIEW OF BASIC POWER FLOW APPROACHES

The major load flow algorithms in most commercial EMS are N-R method, fast decoupled method, or both. All of the derivation details of conventional approaches are found in Book [9]. A single slack bus with generation supply must be selected to apply for power flow analysis.

In the conventional N-R method, as one of nodal-oriented load flow methods, the bus voltages and bus injection powers are chosen to express the power balance equations in polar form or in rectangular form. The power balance equations of a power system in polar form are illustrated, as in:

$$P_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} \left| V_i V_j Y_{ij} \right| \cos(\delta_i - \delta_j - \theta_{ij}), \qquad i = 1,2,...,n \tag{1}$$

$$Q_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} \left| V_i V_j Y_{ij} \right| \sin(\delta_i - \delta_j - \theta_{ij}), \qquad i = 1,2,...,n \tag{2}$$

where, P_i and Q_i are the bus injection real and reactive powers at bus i. Y_{bus} is defined as the $n \times n$ bus admittance matrix composed of the bus self-admittances Y_{ii}, and mutual admittances Y_{ij}. θ_{ij} is the angle of line mutual admittance between bus I, and bus j. δ_i is the phase angles of bus i. n is the total bus number of a system.

Their power mismatch matrix can be written as:

$$\Delta P_i = P_i^{given} - P_i, \qquad i = 1,2,...,n \tag{3}$$

$$\Delta Q_i = Q_i^{given} - Q_i, \qquad i = 1,2,...,n \tag{4}$$

$$\begin{bmatrix} \mathbf{\Delta P} \\ \mathbf{\Delta Q} \end{bmatrix} = \begin{bmatrix} \mathbf{H} & \mathbf{N} \\ \mathbf{M} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \mathbf{\Delta \delta} \\ \mathbf{\Delta V} \end{bmatrix} \tag{5}$$

where the number of P mismatch equations is ‘n-1’, with ‘n’ representing the number of buses in a system, the number of ‘Q’ mismatch equations is ‘n-pvs-1’, where ‘pvs’ is the number of voltage control buses. ‘H,’ ‘N,’ ‘M,’ and ‘L’ are submatrices in the Jacobian matrix. $\mathbf{\Delta\delta}$ and $\mathbf{\Delta V}$ in (5) are solved and then substituted the increments into next iteration to update ΔP_i and ΔQ_i. The element formulas of Jacobian matrix’s submatrices are $H_{ij} = \frac{\partial \Delta P_i}{\partial \Delta \delta_j}, N_{ij} = \frac{\partial \Delta P_i}{\partial \Delta V_j}, M_{ij} = \frac{\partial \Delta Q_i}{\partial \Delta \delta_j}$, and $L_{ij} = \frac{\partial \Delta Q_i}{\partial \Delta V_j}$, respectively. Each iteration goes through the equations from (1) to (5) until convergence.

Using the decoupled techniques, the matrix in (5) can further be simplified into the following forms:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{6}$$

The above incremental power equations in (6) may be directly separated into two parts: P-δ and Q-V:

$$\Delta P/V = [B']\Delta\delta \tag{7}$$

$$\Delta Q/V = [B'']\Delta V \tag{8}$$

where B' is formed by Y_{bus} only, considering line reactance X. B'' is the admittance part of Y_{bus}. The details of derivation process are referenced in [9].

III. DETERMINATION OF PARTICIPATION FACTORS

Although generation bid offers are confidential, it is reasonable to assume that low cost wind and solar power provide the most economical generation dispatch profiles, despite their limitations and uncertainties. Therefore, for the bulk system to truly perform as a resilient power system, it must include a significant portion of renewable resources during normal or emergency operations.

As an individual participant in the market, each generation owner has their own business strategy represented in their generation offers. In a conventional power system, a single slack bus with a generation unit monopolistically responds to real power changes (including transmission losses) for the entire system. However, this single slack bus approach cannot work well with a more diverse generation profile. Conventional power flow methods must be improved to confront the challenges from mixed types of generation and the difficulty of integrating a growing number of renewable generation profiles on their existing EMS. Some generators claim that distributed slack buses concept are implanted in their new EMS version, but power flow balances, voltage regulating control, and contingency analysis test results are not truly satisfied with real time daily operation or renewable energy resiliency characters. The best way is simply to modify the load flow solution methods in the existing system and make them fit to the changes of a power system. The proposed distributed slack bus approach provides a way to satisfy this utility need during power system operation. The operational goal of a power system is to minimize its operation cost, with reliability control in voltage and frequency. The following mathematical functions represent this power system objective:

Minimize $$F_T = \sum_{i=1}^{GN} F_i \tag{9}$$

Subject to

$$\sum_{i=1}^{GN} P_{Gi} = P_{load}^{total} + P_{loss}^{total} \tag{10}$$

$$P_{\min Gi} \le P_{Gi} \le P_{\max Gi} \tag{11}$$

$$P_{\min l} \le P_l \le P_{\max l} \tag{12}$$

where F_T is the total generation costs for system.

P_l is the power flow in each line l.

P_{load}^{total} is the system load.

P_{loss}^{total} is the total transmission loss of the system.

F_i is a unit joining in the utility i of the system.

GN is the number of the participating generators.

Equation (10) represents the key tenet of power flow: that the real system power must always be balanced. Assuming the changes of total transmission loss, generation power and the load as ΔP_{loss}, ΔP_{Gi} and ΔP_{loadj}, the real power balance equation in (10) becomes an incremental balance equation of generation and system loss in (13):

$$\sum_{i=1}^{GN} \Delta P_{Gi} = \Delta P_{loss} + \sum_{j=1}^{LDN} \Delta P_{loadj} \tag{13}$$

When the system load as an operational demand is given in normal operation, its incremental real power balance equation can be rewritten as:

$$\sum_{i=1}^{GN} \Delta P_{Gi} = \Delta P_{loss} \tag{14}$$

In (14), all generators respond to the changes from total generation and total losses. The function of slack bus is merely a reference for phasor angle, and can be randomly selected. This differs from the function of a slack bus in conventional power flow solution methods, where the generator on the slack bus responds to the changes of real and reactive power (including the total line loss), but also acts as a reference for the initial system phasor angle. To easily present how to reform the distributed slack bus power flow solution method, the bus 'n' is defined as the slack bus, the same as common conventional methods. Generator N_G is also assigned to the generator at the slack bus 'n'.

The participation factor of each generating unit is calculated, including transmission loss impact, in the following:

$$k_i = \frac{P_{Gi}}{P_{load}^{total} + P_{loss}^{total}} \tag{15}$$

The net imbalance real power in (14) actually comes from two parts: generation and transmission line loss. The total line loss in a power system will be a function of the choices made through resource management and generation dispatch elections. In most times, total line loss may be estimated at about three- to five-percent of total system load, or neglected in the power flow analysis. The participation factor in (15) can be simplified as:

$$k_i = \frac{P_{Gi}}{P_{load}^{total}} \tag{16}$$

where P_{Gi} is the relevant schedule or forecast generation. k_i is its participation factor. The participation factors in a power system should be satisfied as $\sum k_i = 1$.

The market participants offer their generation resources based on their market strategy. By using the slack bus to balance the real power in the whole system, the traditional algorithms do not adapt to the practical requirements of a restructured power system. The proposed approach will proportionally adjust the generation dispatch over all generators, using participation factor k_i to keep the power balance in a system. This means that the slack bus generator will play the same role as other generators during this process. Resource types, resilience requirements, generation offers and operational reliability criteria are involved in the participation factor calculation. This paper will use the participation factors in (16) to improve the current power flow approaches in the following section.

IV. DEVELOPMENT OF DISTRIBUTED SLACK BUS LOAD FLOW APPROACHES

In power systems, the net imbalance generation power in (14) presents how all generators work together to supply power for this imbalance. To make real power adjustment feasible without degrading the power quality and system reliability, the imbalance power flow of the whole system needs to be balanced in response to the optimal goal. The real power in the system is allocated among these units, based on participation factors, k_i, which are determined by generation schedules and forecasted system load as in (16). All generating units participate in the process of balancing the interconnected system, in response to uncertainties by the load frequency control (LFC) and automatic generating control (AGC). In order to reflect this concept on load flow studies, the proposed new approach will be separately discussed in the N-R load flow and fast decoupled power flow.

A. Distributed Slack Bus Is Embedded into the Newton-Raphson Method

When DP_{total} is defined as the unknown imbalance real power in a power system network, the increment real power balance equation in (14) is rewritten below:

$$\Delta DP_{total} = \sum_{i=1}^{GN} \Delta P_{Gi} \tag{17}$$

Here ΔDP_{total} is the increment of DP_{total} and is added into generator bus mismatch equation in (3) as an unknown variable.

Because the unknown imbalance real power DP_{total} mainly affects the real power in the system, the real power at generator bus *i* may be expressed as:

$$P_{Gi} = P_{Gi}^{0} + k_i \Delta DP_{total}, \quad i = 1.2\ldots, N_G \tag{18}$$

The P-δ load flow formulation of N-R method in (5) has included a new unknown variable DP_{total} and this derivation of the new variable is placed at the last row and last column. The Jacobian formulation of the N-R method can become:

$$\begin{bmatrix} \mathbf{\Delta P} \\ \mathbf{\Delta Q} \\ --- \\ \Delta P_n \end{bmatrix} = \begin{bmatrix} \mathbf{H} & \mathbf{N} & | & \dfrac{\partial \mathbf{P}}{\partial DP_{total}} \\ \mathbf{M} & \mathbf{L} & | & \mathbf{0} \\ -- & -- & - & ---- \\ \dfrac{\partial P_n}{\partial \boldsymbol{\delta}} & \dfrac{\partial P_n}{\partial \mathbf{V}} & | & \dfrac{\partial P_n}{\partial DP_{total}} \end{bmatrix} \begin{bmatrix} \mathbf{\Delta \delta} \\ \mathbf{\Delta V} \\ ----- \\ \Delta DP_{total} \end{bmatrix} \tag{19}$$

When $\dfrac{\partial P_i}{\partial DP_{total}} = k_i$ is the participation factor at bus 'i' with a generation resource, the approach in (19) is called "the distributed slack bus Newton-Raphson power flow method". If that bus has no more generation that is able to be dispatched, its participation factor will be zero. Looking at (19), the modified N-R method with distributed slack buses keeps all of its original N-R advantages, improves voltage magnitudes and phase angles, and embeds the idea into the conventional N-R method in existing EMS.

B. Distributed Slack Bus Is Embedded in Decoupled Power Flow

When decoupled techniques are applied, the off-diagonal submatrices are neglected, as shown in (6). The reactive power part of Jacobian equations stays the same as in (8), but the real power part must be changed. Assuming that the slack bus number of the system remains at bus 'n,' the real power part of the distributed slack bus decoupled power flow is written as:

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_n \end{bmatrix} = \begin{bmatrix} \dfrac{\partial P_1}{\partial \delta_1} & \cdots & \dfrac{\partial P_1}{\partial \delta_{(n-1)}} & \dfrac{\partial P_1}{\partial DP_{total}} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ \dfrac{\partial P_n}{\partial \delta_1} & \cdots & \dfrac{\partial P_n}{\partial \delta_{(n-1)}} & \dfrac{\partial P_n}{\partial DP_{total}} \end{bmatrix} \begin{bmatrix} \Delta \delta_1 \\ \vdots \\ \Delta \delta_{n-1} \\ \Delta DP_{total} \end{bmatrix}$$

(20)

Further, applying the fast decoupling technique to (20) will derive the real power part of the fast decoupled distributed slack bus power flow model:

$$\begin{bmatrix} \frac{\Delta P_1}{V_1} \\ \cdots \\ \frac{\Delta P_{n-1}}{V_{n-1}} \\ --- \\ \frac{\Delta P_n}{V_n} \end{bmatrix} = \begin{bmatrix} & \vdots & \frac{\partial P_1}{V_0 \partial DP_{total}} \\ B'_{(n-1)(n-1)} & & \cdots \\ & \vdots & \frac{\partial P_{n-1}}{V_0 \partial DP_{total}} \\ ----- & & --- \\ B'_{n1} \cdots B'_{n(n-1)} & \vdots & \frac{\partial P_n}{V_0 \partial DP_{total}} \end{bmatrix} \begin{bmatrix} \Delta \delta_1 \\ \cdots \\ \Delta \delta_{n-1} \\ --- \\ \Delta DP_{total} \end{bmatrix} \quad (21)$$

where, B' is formed by $Y_{bus,}$ **when** only considering line reactance X.

This distributed slack bus fast decoupled load method is easily reformed when compared with other formulations, though their Jacobian matrices of distributed slack bus load flows in (19) and (21) become non-symmetric. This new method still permits savings in computation time as that in (7), when the solution techniques of handling spare sub-matrices in (21) are applied.

V. EXAMPLE IMPLEMENTATION AND STUDY RESULTS

Although the distributed slack bus concepts apply to most topics in a resilient power system, this paper only focuses on power flow algorithm implementation. To effectively validate the proposed method, the new approach was implemented in a Matlab simulation. The IEEE example includes systems taken from the internet, addressing [12] have been extensively tested over various operating conditions. Only the IEEE 30 bus system is used as an example in this paper. The characteristics of this IEEE 30 bus system have been simplified for simulation. The modifications include changing synchronous condenser units to generation units, and changing the slack bus number to bus 30, as described in Table I. The network branch parameters were kept the same as those given in [12]. The convergence tolerance is 10^{-3} as the default convergence tolerance. In this test case, the participation factor of each generator is simply computed based on their initial generation values divided by total system load. Table II provides the simulation results and participation factors calculated for each generator. The number of convergence iterations of the proposed approach is almost the same as with the conventional method. The new approach has less system loss and less phase angle difference, when compared to the conventional power flow algorithm. The voltage magnitude and its phase angle profiles in Fig. 1 and Fig. 2 emphasize the distributed slack bus influence in voltage. In those figures, FDLF is the acronym of the conventional fast decouple load flow and DSBLF is the acronym of distributed slack bus load flow. The max voltage difference between DSBLD and FDLF is below 0.007pu. Smaller voltage phasor angle differences utilizing the DSBLF method demonstrate the advantage of distributed slack bus in reliability. The voltage magnitudes are almost the same in the two methods. Generally in tests, the proposed distributed slack bus power flow provides a much better performance than the conventional method. With the new approach, generation reaches a desirable optimal solution in an electric power market.

TABLE I. THE MODIFIED IEEE 30 BUS TEST SYSTEM DESCRIPTION

Bus Number	30
Generation Number	6
Branch Number	43
Total Load in MW	283.4
Total Available Units in MW	425

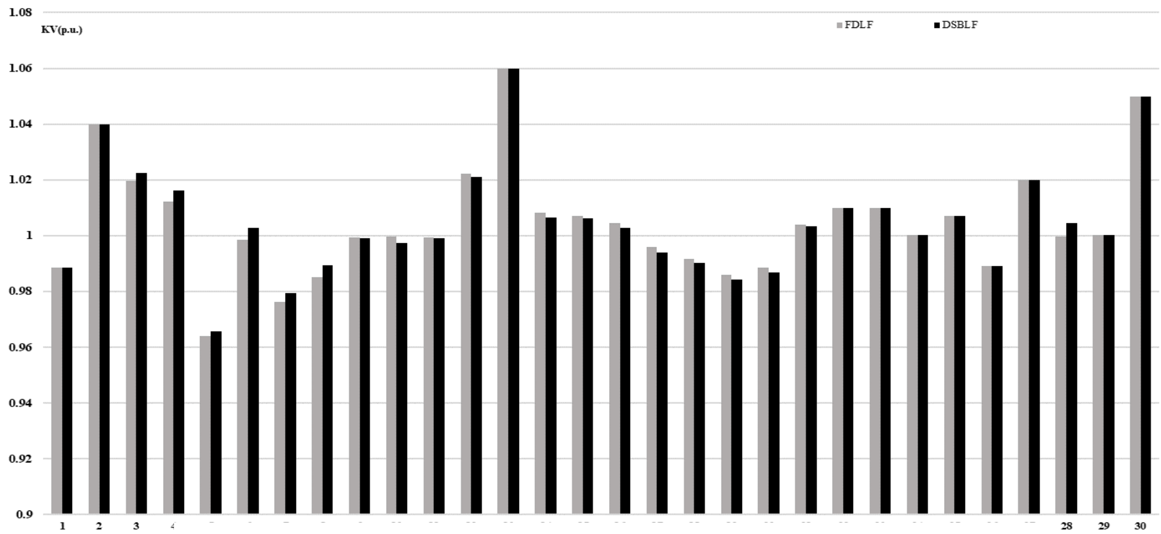

Figure 1. Bus Voltage Magnitudes Comparison of FDLF and DSBLF

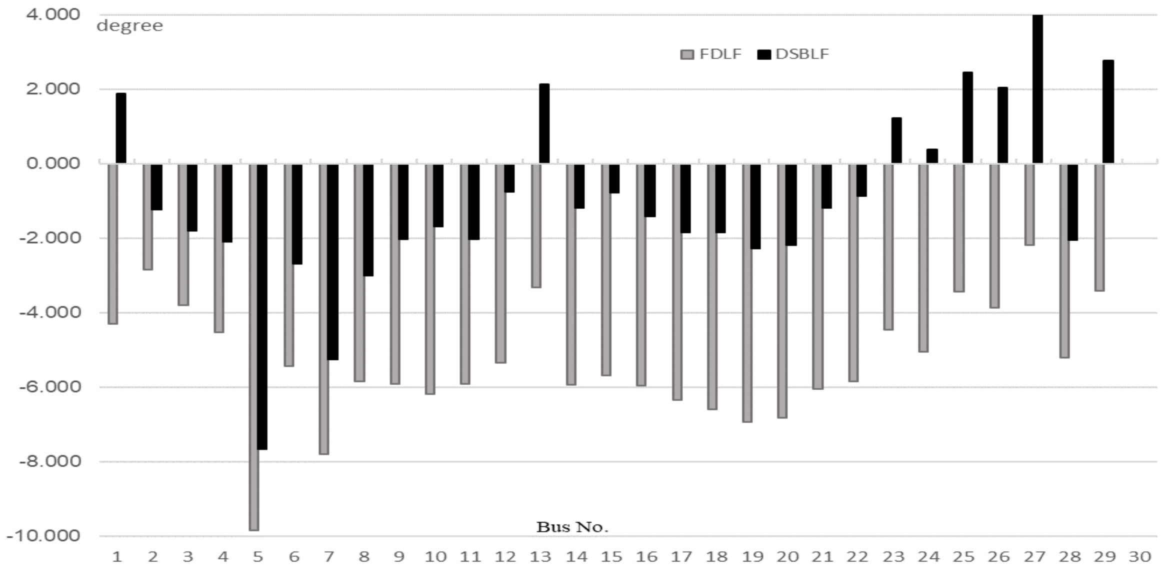

Figure 2. Voltage Phasor Angle Comparison of FDLF and DSBLF

TABLE II. COMPARISON OF FDLF AND DSBLF IN GENERATION PERFORMANCE

G bus	**|V|**	**P_{max} (MW)**	**Fast Decoupled LF**			**Distributed Slack Bus LF**			
			angle	**P(MW)**	**Q(MVR)**	**k**	**angle**	**P(MW)**	**Q(MVR)**
2	1.04	100	-2.8316	53.50	56.89	0.1833	-1.2245	75.57	40.17
13	1.06	50	-3.3080	27.50	29.17	0.0942	2.1431	38.85	30.50
22	1.01	60	-5.8472	25.00	26.70	0.0856	-0.8676	35.31	26.23
23	1.01	35	-4.4619	17.00	-1.52	0.0582	1.2301	24.01	-4.38
27	1.02	60	-2.1774	38.00	9.57	0.1302	4.0096	53.68	8.46
30	1.05	120	0.0000	130.97	8.09	0.4487	0.0000	62.83	24.50
Total P/Q		425		291.97	128.90			290.25	125.49

VI. CONCLUSION

Since the concepts and principles of resilient power system operation differ from those of traditional power system operation, the traditional bus-oriented power flow algorithms applied in commercial standard EMS need to be modified to meet the new requirements for system control and management. A new distributed slack bus power flow formulation is proposed to deal with the challenges of a resilient power grid. It permits EMS owners to easily reform the traditional N-R and fast decoupled power flow methods to analyze power flow in real time and planning. Participation factors are used to allocate all transactions to transmission operations participants. The new formulation basically keeps the traditional bus-oriented power flow algorithm, using bus voltage magnitudes and phase angles as independent variables, while requiring the slack bus to be added as a variable. This simple reformation can promote current EMS to work in the resilient structures, without necessitating elaborate changes in the existing algorithm. This proposed method optimally allocates generation using participation factors, and helps market participants generate more power than previous dispatch patterns, through optimization planning alone. The results from the example system of IEEE 30 buses demonstrate the capability of this new approach. Comparative studies of voltage profiles show that the new formulation is equally as accurate as the conventional formulation. The new formulation also promises improved solutions to optimize power grid benefits. This algorithm affords great potential in improving the EMS for the new operational environment, as well as real time constrained optimization of power flow analysis. More comprehensive testing and studies are underway. The major advantages of this proposed method include no significant modifications in the conventional load flow algorithms, high computation speed and more effective power flow analysis in a power system mix.

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