

Optimal Power Flow Incorporating Frequency Security Constraint

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Abstract—Optimal power flow (OPF) minimizes the production cost while satisfying the constraints on the system, such as real and reactive power balance, equipment capability constraints, and voltage limits. This paper presents a method of incorporating a frequency security constraint within the framework of the OPF problem. Increasing displacement of conventional generation by renewable resources that contribute little or no frequency regulation capability may necessitate the enforcement of such a constraint to meet frequency security requirements. The system frequency is required to be maintained within a safe limit, thus indicating the balance between generation and consumption. Hence, the solution for optimization of power flow should not only present a minimum cost of generation within the operating conditions, but also ensure frequency stability. In order to obtain this solution, the requirement of frequency stability is introduced as a new constraint of the power dispatch problem and is represented by the maximum frequency deviation limit. This new constraint is constructed as a non-linear function of system inertia and the frequency regulation constant, since frequency deviation is highly sensitive to these factors. It is shown that the inclusion of this constraint causes the OPF to preferentially select higher inertia generators as necessary, to satisfy the frequency security requirement. A genetic algorithm is utilized as the optimization tool in this work. The IEEE RTS-79 test system is used to demonstrate efficacy of the proposed method.

Index Terms—Equivalent regulation constant, frequency deviation, frequency security, inertia, optimal power flow.

I. INTRODUCTION

WITH increasing penetration of variable resources such as wind and solar energy, the issue of frequency security is becoming a matter of growing concern. The North American Electric Reliability Corporation (NERC) has established certain standards for frequency security [1], [2]. To address the system frequency security, a number of stability studies and approaches have been proposed and implemented in the literature [3], [4]. The frequency deviation limits can be used to enforce the system frequency security, among other benchmarks [4]–[7]. To maintain frequency within safe limits, the system must have enough spinning reserve and inertia. However, with the high level of generation diversity in modern power systems, frequency security faces new challenges due to the deficiency of inertia and regulation capacity [8]–[12].

Hence, the solution of the optimal power flow must take into account the influence of the frequency security.

Optimal power flow is used in almost all modern power pools. While the objective function may consist of social welfare to be maximized in competitive markets or of production cost to be minimized in regulated pools, the remainder of the OPF framework is very similar across pools, consisting of operating constraints. In this work, we shall work with the OPF framework assuming that the objective is to minimize production cost. Although the least cost dispatch solution usually satisfies normal operating conditions, it may still cause a violation of frequency security, due to the lack of frequency regulation capacity. In [13], [14], the North American Electric Reliability Corporation and the Electric Reliability Council of Texas have reported a reduction in frequency response due to an increase in distributed generation. This motivates the development of an OPF framework that includes frequency security constraints.

In its most general form, OPF seeks to minimize production cost (or maximize social welfare) subject to equality constraints describing real and reactive power balance, and inequality constraints that include equipment capability constraints, voltage magnitude limits, and other operating conditions defined by the pool rules. In addition to these, transient stability constraints have also been considered in the OPF problem in [15], [16] so that the system is transiently secured for the given generation dispatch. The OPF problem with voltage stability and demand response constraints was also addressed in [17]. Large-scale security-constrained OPF with a contingency filtering scheme was presented in [18]. In [19], the frequency stability constraint is considered in the OPF so that the frequency deviation of a system stays within a safe limit under normal condition.

Over the last five decades, numerous methods have been proposed to solve the OPF problem. A variety of methods have been employed including Newtonian methods [20], interior point methods [21], non-deterministic and hybrid methods [22], sequential quadratic programming [23], genetic algorithm [24], [25], linear approximations [26], convex transformation techniques and Taylor series [27], flexible mixed-integer linear programming approach [28], and chordal conversion based convex iteration [29]. Although the authors in [30] proposed to include frequency security, a DC flow based model was utilized and hence reactive power balance and voltage limits were not considered. Further, the frequency security constraint had to be linearized to enable implementation in the problem.

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In this paper, the OPF framework is expanded to include the frequency security constraint in the optimization problem with a full set of system operational constraints. Here, OPF not only minimizes the production cost, but also preferentially dispatches higher inertia generators to compensate for inertial generation displaced by renewable generation. This security constraint is developed using the maximum frequency deviation and system inertia along with the regulation constant. It is shown that the inclusion of this constraint causes the OPF to preferentially select higher inertia generators as necessary, to satisfy the frequency security requirement. Although previous studies have considered stability constraints in OPF, none of them has so far developed the mathematical model of frequency stability constraint and implemented it as a nonlinear constraint in the OPF problem. This is the main contribution of this paper. The effect of the constraint developed here is shown using a disturbance in the form of a load change; similar perturbations result from reliability events such as loss of generation. In the past, there was sufficient inertial generation that frequency deviations rarely exceeded the limits, and the inclusion of a frequency security constraint was not considered necessary. However, in recent times, with increasing displacement of inertial generation, the need for measures to ensure frequency stability is being realized. The California ISO (CAISO) has just released a proposal for a frequency response standard [31], which requires CAISO to provide sufficient frequency response. Our work addresses these issues, and contributes a solution toward the development of such a requirement.

To solve the OPF, a genetic algorithm is utilized. Genetic algorithm (GA) is a popular approach in power systems that generates high-quality solutions [32]–[36]. GA provides a powerful search mechanism while maintaining simplicity. It also has the ability to avoid locally optimal solutions to reach the globally optimal solution. Moreover, GA has the advantage of dealing with different types of functions and constraints. An important contribution of this paper is to model the frequency security as a non-linear constraint. The application of GA aids in avoiding linearization due to its ability to handle both linear and non-linear constraints.

The remainder of this paper is organized as follows. In section II, the mathematical model of the OPF has been developed. In addition to the frequency security constraint, other operational constraints have been considered, such as the real and reactive power balance, the limits of the generators, the limits of bus voltages, the reserve constraint. The implemented simulation model and its results are presented in section III. A comparison between the results obtained from the proposed method and previous methods has been shown to support the claims of this paper. Finally, some concluding remarks have been provided in section IV.

II. OPTIMAL POWER FLOW PROBLEM IN THE PRESENCE OF FREQUENCY SECURITY CONSTRAINT

The purpose of OPF is to find the dispatch solution to minimize production cost (or maximize social welfare) under a set of physical inequality and equality constraints created

by the operating conditions and the limits of the equipment. The equality constraints include real and reactive power balance, and inequality constraints include equipment capability constraints, voltage magnitude limits, and other operating conditions defined by the pool rules. The construction of the OPF problem is shown as follows:

A. Problem Objective

As stated earlier, it is assumed in this work that the OPF problem seeks to minimize production cost. A second-order quadratic polynomial is used to represent the total fuel cost (\$/hr) for the generators in the system [32]:

$$\sum_{i \in S} C_i = \sum_{i \in S} (a_i (P_i^G)^2 + b_i P_i^G + c_i) \quad (1)$$

where C_i is the fuel cost, P_i^G is the power output, and a_i, b_i, c_i are coefficients of generator i . S is the set of dispatched generators in the system.

B. Problem Constraints

The power flow in the system must satisfy some constraints to be able to maintain the operating conditions. These constraints include the balancing of load and generation, limiting the bus voltages, and maintaining a sufficient amount of spinning reserve for reliability and stability purposes. In addition to these, this paper introduces another constraint that is mostly neglected in the OPF—the frequency security constraint. The constraints included in the proposed OPF formulation are as follows:

- Power balance: the power at each bus in the system must equal the difference between generation and load at that bus:

$$P_i(V, \delta) = P_i^G - P_i^L \quad \forall i \in N \quad (2)$$

$$Q_i(V, \delta) = Q_i^G - Q_i^L \quad \forall i \in N \quad (3)$$

where

$$P_i(V, \delta) = V_i \sum_{k \in N} V_k (G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k))$$

$$Q_i(V, \delta) = V_i \sum_{k \in N} V_k (G_{ik} \sin(\delta_i - \delta_k) - B_{ik} \cos(\delta_i - \delta_k))$$

P_i and Q_i are real and reactive powers at bus i ; V_i and V_k are the voltage magnitudes at buses i and k ; δ_i and δ_k are the voltage angles of buses i and k ; G_{ik} and B_{ik} are the real and reactive parts of the element $Y(i, k)$ of the bus admittance matrix Y ; N is the set of all buses in the system.

- Generating capability and voltage magnitude limits:

$$P_i^{G, \min} \leq P_i^G \leq P_i^{G, \max} \quad \forall i \in S \quad (4)$$

$$Q_i^{G, \min} \leq Q_i^G \leq Q_i^{G, \max} \quad \forall i \in S \quad (5)$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad \forall i \in N \quad (6)$$

where $P_i^{G, \min}$ and $P_i^{G, \max}$ are the minimum and maximum real power capabilities; $Q_i^{G, \min}$ and $Q_i^{G, \max}$ are the minimum and maximum reactive power capabilities

of the generator i ; V_i^{min} and V_i^{max} are the minimum and maximum voltages at bus i .

- Transmission line limits: constraints for transmission lines are represented as the limits of real power flow that can be transmitted between two terminals of those lines:

$$P_{ij} \leq P_{ijmax} \quad \forall i \in M \quad (7)$$

where

$$P_{ij} = V_i^2 |Y_{ij}| \cos \theta_{ij} - V_i V_j |Y_{ij}| \cos(\delta_{ij} - \theta_{ij}) \quad (8)$$

θ_{ij} is the angle of (i, j) element of bus admittance matrix Y , while M is the set of all transmission lines in the system.

- Spinning reserve requirement: due to the variation of the demand, the system must maintain a minimum quantity of spinning reserve to ensure system stability and reliability. The spinning reserve constraint is constructed as follows:

$$\sum_{i \in N} (P_i^{G,max} - P_i^G) \geq \epsilon_1 P_{lup}^G \quad (9)$$

$$\sum_{i \in N} (P_i^G - P_i^{G,min}) \geq \epsilon_2 P_{ldown}^G \quad (10)$$

where ϵ_1 and ϵ_2 are the upper and lower rotating standby rates of the system; P_{lup}^G and P_{ldown}^G are the demands when the upward and downward spinning reserve is needed.

- Frequency security constraint: following an unexpected disturbance within a power system, the frequency starts deviating from the nominal value. Inertia, load damping, and other damping mechanisms immediately inhibit the frequency deviation. The governor adjusts the generator output to prevent frequency from deviating further. The output of the generator is changed by regulating the prime mover input. The maximum frequency deviation, and a part of the frequency recovery duration is attributed to these actions. This mechanism is a part of the load frequency control (LFC), which eventually restores the frequency to the nominal value, if the system has sufficient reserve. The maximum frequency deviation and the recovery duration of frequency are inversely proportional to the system inertia (H) and load damping (D), which has been illustrated in Fig. 1. Therefore, in order to maintain the frequency within a safe limit, a minimum amount of inertia is vital to the system. For this reason, a frequency security constraint should be considered in the OPF problem.

In [37] and [30], a generalized model of LFC capable of representing each governor contribution to the system frequency control was proposed. This LFC model was constructed based on the sensitivity of frequency deviation to the governor parameters for the low-order LFC model in [38], of which the accuracy has been evaluated. The model of LFC for the multi-machine system is shown in Fig. 2.

In Fig. 2, the notations used are as follows:

- H = equivalent inertia constant
- D = load damping constant
- K_i = LFC controller of machine i

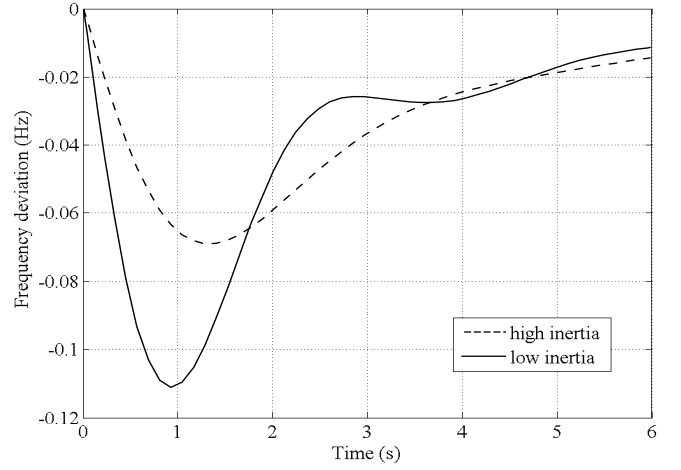


Fig. 1: Frequency deviation with different values of inertia.

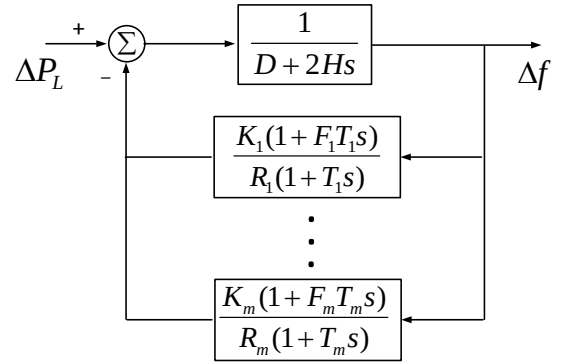


Fig. 2: LFC model of a multi-machine system [30].

- R_i = equivalent regulation constant of machine i
- F_i = fraction of turbine power generated by HP unit of machine i
- T_i = governor time constant of machine i
- Δf = frequency deviation
- ΔP_L = disturbance

In this model, inertia constant H is the sum of the ratios of the kinetic energy and the rating of the rotor for each synchronous machine. All governor time constants are assumed to be of identical value. This assumption is reasonable and it has very little effect on the accuracy of the model due to the low sensitivity of the maximum frequency deviation to the governor time constant T_R [30].

From the LFC model for the multi-machine system, the equation of frequency deviation can be constructed as follows:

$$\Delta f(s) = \frac{\frac{\Delta P_L}{s}}{D + 2Hs + \sum_{i=1}^m \frac{K_i(1+F_i T_R s)}{R_i(1+T_R s)}} \quad (11)$$

With the assumption that all values of T_R for the system governors are identical, equation (11) can be rewritten as [30]:

$$\Delta f(s) = \frac{\Delta P_L}{2HT_R s} \frac{1 + T_R s}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (12)$$

where

$$F_R = \sum_{i=1}^m \frac{K_i F_i}{R_i} \quad (13)$$

$$R_R = \sum_{i=1}^m \frac{K_i}{R_i} \quad (14)$$

$$\omega_n = \sqrt{\frac{1}{2HT_R}(D + R_R)} \quad (15)$$

$$\zeta = \frac{1}{2} \frac{2H + T_R(D + F_R)}{\sqrt{2HT_R(D + R_R)}} \quad (16)$$

The following expansion enables the inverse Laplace transform of (12):

$$\Delta f(s) = \frac{\Delta P_L}{2HT_R s} \frac{1}{s^2 + 2\zeta\omega_n s + \omega_n^2} + \frac{\Delta P_L}{2H(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad (17)$$

From equation (17), the equation of frequency deviation in the time-domain can be obtained as:

$$\Delta f(t) = \frac{\Delta P_L}{2HT_R\omega_n^2} \left(1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \cos(\omega_n \sqrt{1-\zeta^2} t - \phi)\right) + \frac{\Delta P_L}{2H\omega_n \sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin(\omega_n \sqrt{1-\zeta^2} t - \phi) \quad (18)$$

where

$$\phi = \tan^{-1}\left(\frac{\zeta}{\sqrt{1-\zeta^2}}\right) \quad (19)$$

When the frequency deviation reaches its maximum value, its derivative equals zero:

$$\frac{d\Delta f(t)}{dt} = 0 \quad (20)$$

Hence, the maximum frequency deviation and the corresponding time instant can be derived as follows:

$$t_{max} = \frac{1}{\omega_n \sqrt{1-\zeta^2}} \tan^{-1}\left(\frac{\omega_n \sqrt{1-\zeta^2}}{\zeta\omega_n - 1/T_R}\right) \quad (21)$$

$$\Delta f_{max} = \frac{\Delta P_L}{R_R + D} \left(1 + e^{-\zeta\omega_n t_{max}} \sqrt{\frac{T_R(R_R - F_R)}{2H}}\right) \quad (22)$$

Once the equation for maximum frequency deviation is determined, the frequency security constraint is developed based on the requirement of maintaining the frequency deviation within these safe limits:

$$-\Delta f_s \leq \Delta f_{max} \leq \Delta f_s \quad (23)$$

The variation in the inertia of the generators will change the maximum frequency deviation. The system inertia is determined as follows.

If a generator i is synchronized (generator i dispatches in the system), the inertia of generator i is included in total inertia of the system. Otherwise, inertia of generator i is not included. The inertia and equivalent regulation constants are then replaced in equations (13) and (14). The variation of these two elements will affect Δf_{max} . The reduction of inertia results in the increase of the frequency deviation, as shown in equation (22), and decrease otherwise. Hence, equation (23) is used as the security constraint in the OPF problem.

Although the frequency disturbance considered in the proposed method is a load increase, the method can deal with generation tripping as well. Once a generator (say generator i) in the system trips, the contribution of generator i in load frequency control will be neglected (H_i, R_i, F_i, T_i, K_i). For this case, the maximum frequency deviation is changed in equation (22), and this value of frequency is used in the frequency security constraint. The system will maintain the frequency security by involving other units in dispatch process and the proposed method will still be in effect.

Not only is the proposed method applicable to a system with only conventional generation, but also to a system integrated with renewable energy resources (RERs). Considering the low or near-zero inertia and intermittent nature of RERs, they have limited ability to support frequency control. However, with the application of some advanced control strategies, RERs can mimic a conventional generator with its low synthetic inertia when its available output is different from zero [39]. Hence, the proposed method is still in effect.

III. SIMULATION AND RESULTS

The proposed method is tested on the IEEE RTS-79 system to show the impact of frequency security requirement on the OPF. IEEE RTS-79 test system is chosen for simulation since it includes many generators with different capacities, cost, and inertia values. Moreover, different generators are grouped into one generation bus creating a diversity of generated cost at each bus. The IEEE RTS-79 is described below, and the system data is shown in Table I.

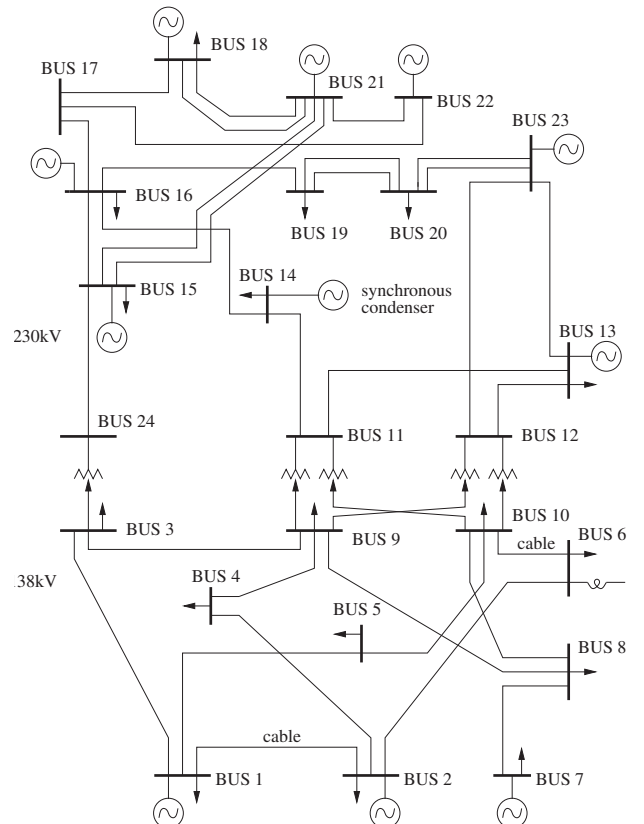


Fig. 3: Single line diagram of IEEE RTS-79 test system.

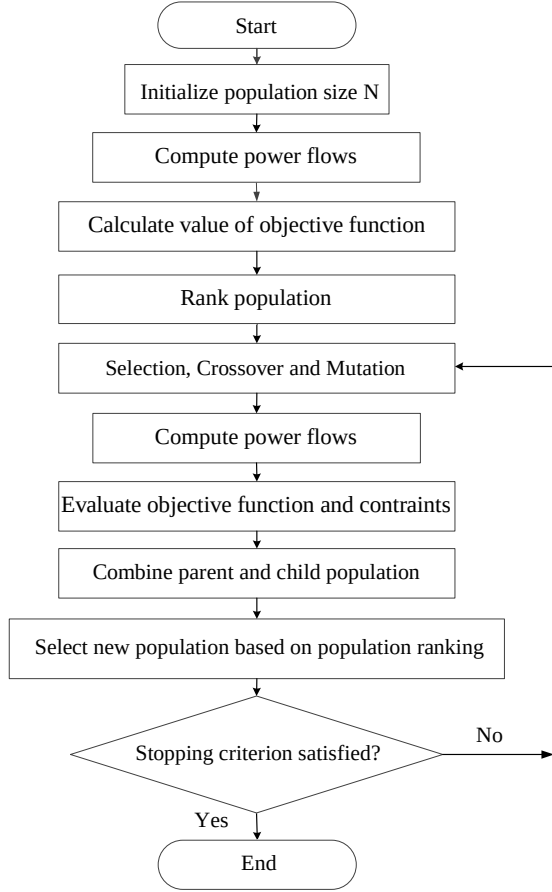


Fig. 4: Genetic algorithm in optimal power flow.

A. System Configuration

The IEEE-RTS system includes 32 conventional generators with a total capacity of 3405 MW. There are 10 generation buses and 16 load buses with 36 transmission lines. The total maximum load demand of the system is 2850 MW. The generator cost coefficients, active and reactive power limit values and dynamic data of 32 generators are presented in Table I [40], [41]. More detailed information regarding the IEEE RTS-79 system can be found in [41]. The load damping value of the system is assumed to be 2 p.u. Load disturbance is simulated by a 0.1 p.u. step function. The maximum frequency deviation is constrained within ± 0.1 Hz [5] of nominal frequency to maintain frequency security. The IEEE RTS-79 system is shown in Fig. 3 [41].

B. Simulation Results

Genetic algorithm (GA) is utilized to demonstrate the proposed idea. Although the OPF formulation presented above can be solved by any non-linear optimization method, GA has been used as it provides a powerful search mechanism, while maintaining simplicity. It has enough inherent perturbations that allows it to avoid getting stuck in the neighborhood of locally optimal solutions. Also, it is not restricted by the

dispositions of the function, such as continuity, existence of derivatives, etc. The algorithm is implemented in MATLAB and is described by the flowchart in Fig. 4. The algorithm terminates when it satisfies the following stopping criteria:

- The difference between the best costs of two consecutive sets of population equals zero.
- The difference between variances of two consecutive sets of population is smaller than a specified limit.

To show the impact of frequency security on the OPF solutions, two case studies are presented:

- Case study 1: The OPF problem is solved without the consideration of frequency security constraint for six load scenarios.
- Case study 2: The frequency security constraint in equation (23) is included in the OPF formulation to ensure that the maximum frequency stays within the specified limits.
- Case study 3: In this case, OPF with generation tripping is modeled with and without frequency security constraint.
- Case study 4: OPF with wind generation is implemented with and without frequency security constraint.

Case study 1: Due to the variation of the load, eight load scenarios are simulated for the system. The load is chosen to vary from 40% to 100% of maximum total load with a step of 5%, 10%, and 20%. The purpose of changing the load is to show the different solutions of the OPF problem and different impacts of frequency security constraint on the OPF solution. For each load scenario, the OPF is implemented and it is checked whether there is a violation of the frequency security constraint. The solutions for the eight load scenarios are shown in Table II. The results show the total generation at each generation bus, total generation of the system and the total cost. The results also show whether each load scenario violates the frequency security constraint. The units enrolled in dispatch at each bus for each scenario for this case study are shown in Table IV. The frequency deviation in time frame for six load scenarios without frequency security constraint are shown in Fig. 5 to compare the difference in frequency response for different load scenarios.

As shown in Table II and IV, when the loads are at or above 85% of the peak load, most of the generators are dispatched. Therefore, the system inertia increases and the frequency security constraint is satisfied. However, when the loads are at or below 80% of the peak load, the OPF solution does not satisfy the frequency security constraint.

Case study 2: In this case, the secure OPF framework, which includes the frequency constraint, is used. The results for the load scenarios 85% and above are the same as the regular OPF, as shown in Table III and V. For the load scenarios that have the violated frequency deviation, the OPF solution that includes the proposed constraint is shown in Table III, which is different from the solution in Table II. The units which enroll in dispatch at each bus for each scenario in this case are shown in Table V. The frequency responses for the secure OPF with load below 80% of the peak load are shown in Fig.

TABLE I: Cost coefficients, power and voltage limits, and dynamic data of 32 generators

Gen_i	Bus	Number of units	a_i	b_i	c_i	P_i^{min} MW	P_i^{max} MW	Q_i^{min} MVAR	Q_i^{max} MVAR	V_i^{max} p.u.	V_i^{min} p.u.	H_i p.u.
12	15	5	0.328412	56.564	86.3852	0	12	0	6	0.95	1.05	0.34
20	1, 2	2, 2	0	130	400.6849	0	20	0	10	0.95	1.05	0.56
50	22	6	0	0.001	0.001	0	50	-10	16	0.95	1.05	1.75
76	1, 2	2, 2	0.014142	16.0811	212.3076	0	76	-25	30	0.95	1.05	2.28
100	7	3	0.052672	43.6615	781.521	0	100	0	60	0.95	1.05	2.80
155	15, 16, 23	1, 1, 2	0.008342	12.3883	382.2391	0	155	-50	80	0.95	1.05	4.65
197	13	3	0.00717	48.5804	832.7575	0	197	0	80	0.95	1.05	5.52
350	23	1	0.004895	11.8495	665.1094	0	350	-25	150	0.95	1.05	10.5
400	18, 21	1, 1	0.000213	4.4231	395.3749	0	400	-50	200	0.95	1.05	20

6.

Case study 3: In this case, the proposed OPF has been applied to a system with a tripped generator of capacity 50 MW at bus 23. The demand is considered to be 70% of the peak load. The OPF results with and without considering frequency security constraint are shown in Tables II and III.

Case study 4: In this case, two wind farms with 100 MW capacity each are installed at bus 7, with a predicted available capacity of 80 MW. The levelized cost, inertia of the wind farms, and demand are considered to be \$12/MW [42], 0.2 p.u., and 70% of the peak load respectively. The results with and without the frequency security constraint are shown in Tables II and III.

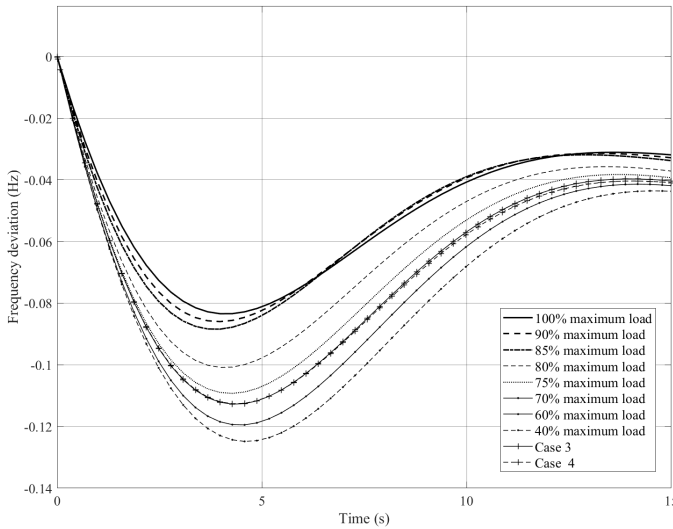


Fig. 5: Frequency deviation for ten load scenarios without considering frequency security constraint.

The results of the simulations are shown in Tables II–V. The italicized entries in Tables III and V highlight the changes in dispatch that result from incorporating the frequency security constraint. From these results, the following can be inferred:

- Comparing the results shown in Table II and Table III, it can be seen that both solutions for the regular OPF and the secure OPF achieve the same results for load scenarios

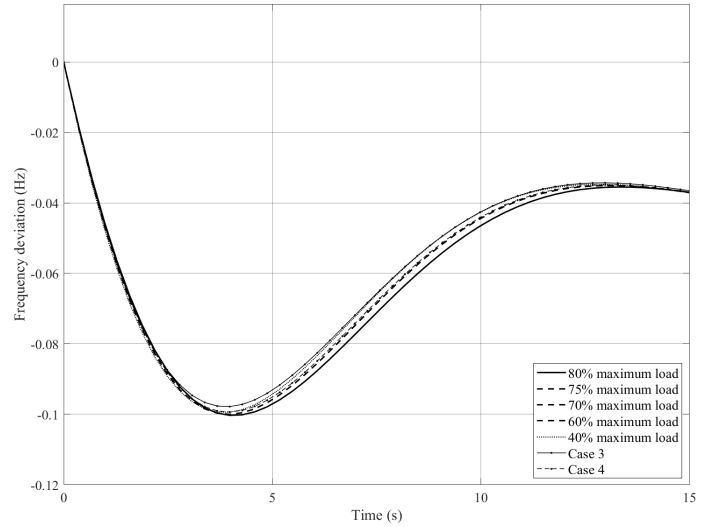


Fig. 6: Frequency deviation for seven load scenarios considering frequency security constraint.

from 85% to 100% of the peak load, since there is no frequency security violation. However, when the load is 80% of the peak load or lower, the solutions are different. This is due to the fact that the feasible region of the solution has changed because of the new constraint. As a result, considering the new constraint, the most economic solution is not the solution that ensures system stability. Therefore, it is important to consider this constraint when dealing with the OPF problem.

- As shown in the OPF solutions in Table II, Table III, Table IV, and Table V, more generators with a higher generation cost enroll in the dispatch at buses 1, 2, 7, and 13, while the other generators with lower generation cost decrease their outputs at buses 22 and 23. This happens as the more expensive generators at buses 1, 2, 7, and 13 help in increasing the inertia level, thus accommodating the frequency security. As a result, the cost increases. When the load is 70% of the peak load, the cost increases from \$28400.21 to \$28734.73. For 75% and 80% of the peak load, the cost increases from \$30843.39 to \$31165, and from \$36319.41 to \$36453.95, respectively. Similar results are obtained when the demand is considered to be

TABLE II: The solutions of the OPF for 10 load scenarios without the frequency security constraint

Load Percentage	Bus 1	Bus 2	Bus 7	Bus 13	Bus 15	Bus 16	Bus 18	Bus 21	Bus 22	Bus 23	Total Gen	Total Cost	Violation?
40	0.0	0.0	0.0	0.0	5.03	5.22	371.98	372.09	284.84	142.70	1181.91	15958.80	Yes
60	10.02	10.06	0.0	0.0	106.39	111.67	371.66	371.71	285.08	503.93	1770.99	23966.23	Yes
70	63.69	64.91	0.0	0.0	144.09	143.79	371.97	372.01	285.41	613.52	2059.70	28400.21	Yes
75	133.67	134.66	0.0	0.0	144.33	144.40	372.11	372.37	285.16	613.78	2199.44	30843.39	Yes
80	141.36	141.32	114.23	0.0	144.18	144.15	372.04	372.07	285.09	613.80	2328.05	36319.41	Yes
85	141.38	141.38	177.48	74.69	144.13	144.16	372.00	372.00	285.07	613.82	2465.89	43041.61	No
90	141.38	141.34	195.61	197.00	144.15	144.15	372.06	372.05	285.11	613.81	2606.43	49978.28	No
100	141.36	141.39	232.31	444.45	144.15	144.13	372.00	372.00	285.01	613.80	2890.58	64256.84	No
Case 3	84.47	84.58	0.0	0.0	143.94	144.12	372.61	372.15	237.50	613.84	2053.65	29110.53	Yes
Case 4	11.37	12.54	193.0	0.0	123.72	128.31	372.00	372.00	285.05	549.35	2046.98	27487.76	Yes

TABLE III: The solutions of the secure OPF for 10 load scenarios considering the frequency security constraint

Load Percentage	Bus 1	Bus 2	Bus 7	Bus 13	Bus 15	Bus 16	Bus 18	Bus 21	Bus 22	Bus 23	Total Gen	Total Cost
40	5.35	10.02	0.0	10.18	5.37	6.15	372.00	372.05	279.95	119.36	1180.84	16422.03
60	10.07	10.02	5.07	5.03	105.12	110.27	371.95	372.06	281.60	498.40	1769.56	24313.02
70	59.93	61.12	5.22	5.00	143.77	144.32	372.48	371.59	281.67	613.80	2058.82	28734.73
75	129.76	130.71	5.01	5.00	144.10	144.98	372.23	371.84	281.67	613.80	2198.25	31165.00
80	141.59	141.67	117.05	0.0	144.60	144.83	372.89	372.09	281.67	613.80	2327.55	36453.95
85	141.38	141.38	177.48	74.69	144.13	144.16	372.00	372.00	285.07	613.82	2465.89	43041.61
90	141.38	141.34	195.61	197.00	144.15	144.15	372.06	372.05	285.11	613.81	2606.43	49978.28
100	141.36	141.39	232.31	444.45	144.15	144.13	372.00	372.00	285.01	613.80	2890.58	64256.84
Case 3	100.98	98.51	12.0	15.24	142.34	135.80	370.61	371.85	236.16	564.74	2048.23	30020.36
Case 4	15.25	16.20	165.04	5.0	127.24	131.54	372.00	372.00	281.67	561.14	2047.03	27952.19

TABLE IV: The dispatched units of the OPF for 10 load scenarios without the frequency security constraint

Load Percentage	Bus 1	Bus 2	Bus 7	Bus 13	Bus 15	Bus 16	Bus 18	Bus 21	Bus 22	Bus 23
40	0	0	0	0	U155	U155	U400	U400	6×U50	U350
60	U76	U76	0	0	U155	U155	U400	U400	6×U50	2×U155, U350
70	U76	U76	0	0	U155	U155	U400	U400	6×U50	2×U155, U350
75	2×U76	2×U76	0	0	U155	U155	U400	U400	6×U50	2×U155, U350
80	2×U76	2×U76	2×U100	0	U155	U155	U400	U400	6×U50	2×U155, U350
85	2×U76	2×U76	2×U100	U197	U155	U155	U400	U400	6×U50	2×U155, U350
90	2×U76	2×U76	3×U100	2×U197	U155	U155	U400	U400	6×U50	2×U155, U350
100	2×U76	2×U76	3×U100	3×U197	U155	U155	U400	U400	6×U50	2×U155, U350
Case 3	2×U76	2×U76	0.0	0.0	U155	U155	U400	U400	5×U50	2×U155, U350
Case 4	U76	U76	U100, 2×W	0.0	U155	U155	U400	U400	6×U50	2×U155, U350

TABLE V: The dispatched units of the secure OPF for 10 load scenarios considering the frequency security constraint

Load Percentage	Bus 1	Bus 2	Bus 7	Bus 13	Bus 15	Bus 16	Bus 18	Bus 21	Bus 22	Bus 23
40	U76	2×U76	0.0	2×U197	U155	U155	U400	U400	6×U50	2×U155 , U350
60	2×U76	2×U76	U100	U197	U155	U155	U400	U400	6×U50	2×U155, U350
70	2×U76	2×U76	U100	U197	U155	U155	U400	U400	6×U50	2×U155, U350
75	2×U76	2×U76	U100	U197	U155	U155	U400	U400	6×U50	2×U155, U350
80	2×U76	2×U76	3×U100	0.0	U155	U155	U400	U400	6×U50	2×U155, U350
85	2×U76	2×U76	2×U100	U197	U155	U155	U400	U400	6×U50	2×U155, U350
90	2×U76	2×U76	3×U100	2×U197	U155	U155	U400	U400	6×U50	2×U155, U350
100	2×U76	2×U76	3×U100	3×U197	U155	U155	U400	U400	6×U50	2×U155, U350
Case 3	2×U76	2×U76	2×U100	U197	U155	U155	U400	U400	5×U50	2×U155, U350
Case 4	2×U76	2×U76	U100, 2×W	U197	U155	U155	U400	U400	6×U50	2×U155, U350

40% or 60% of the peak load.

- Fig. 5 shows that for cases with system loads higher than 80% of the peak load, the maximum frequency deviation still remains within safe limits due to the high inertia of the system. However, when the load is below 80% of the peak load, the maximum frequency deviation exceeds the safe range of frequency deviation. When the frequency security constraint is considered, there is an increase in the amount of inertia enrolled in frequency regulation, and this increase in inertia ensures that the maximum deviation stays within safe limits, as shown in Fig. 6. In case 2, the dispatch result preferentially selects higher inertia generators as necessary, to satisfy frequency security constraint. Also, more generators are deployed so that the total inertia of the system increases although the total load of the first three load scenarios stays the same, as shown in Table V.
- For case 3, when one 50 MW unit is tripped, the consideration of frequency security constraint has the similar impact compared to case 2. The generators with higher cost must be included in the dispatch to ensure the system frequency stability. This increases the total cost of the dispatch solution from \$29110.53 to \$30020.36.
- The results for case 4 with the integration of wind power generation shows that although wind power contributes a small amount of inertia, the frequency constraint is not satisfied with the most economic dispatch solution. The inclusion of frequency security constraint causes an increase in the power output and number of generators enrolled in the dispatch at bus 1, 2 and 13. The maximum frequency deviation of the system with the constraint is within safe limits and is shown in Fig. 6.

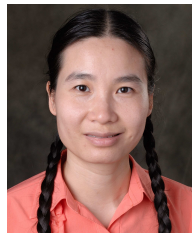
IV. CONCLUSION

In this paper, a mathematical model for the frequency security constraint was developed to ensure a more secure operation of the power system. The OPF problem has been investigated with the consideration of frequency security. The simulation models of the OPF problem with and without the frequency security requirement were implemented to demonstrate the effect of the proposed idea. The results from the mathematical and simulation models show that frequency security impacts the solution of optimal power flow. The analysis and results indicate that it is important to consider frequency security while choosing the optimal economic dispatch solution. This security requirement would benefit the operators in maintaining stability in a system with reduced inertia due to increasing renewable penetration and also benefit the customers by providing improved power quality.

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