Research Article

Frequency Monitoring and Control during Power System Restoration Based on Wide Area Measurement System

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Frequency control during power system restoration has not been strongly addressed. Operators are often concerned with the offline sizing of load and generation steps, but, nowadays, the introduction of Wide Area Measurement System (WAMS) makes it possible to monitor the stability of power system online. The constraints of WAMS operation result in some changes in power system frequency control. This paper proposes a novel methodology for frequency control and monitoring during the early steps of power system restoration based on WAMS. Detailed load modeling is achieved based on the static load modeling approach. Power generators' modeling is also accomplished utilizing the single machine equivalent of the power system based on PMU measurements. Simulation results of the presented methodology on the 39 bus New England power system clearly show the effectiveness and applicability of the proposed method. The simulation results show that the presented approach has a completely acceptable precision and an outstanding speed with less than 0.05% error. The outstanding speed of the presented approach along with the result precision will result in a great promotion in power system restoration methodologies.

1. Introduction

The problem of restoring power systems after a complete or partial blackout is as old as the power industry itself. Restoration of a power system after a system blackout is a complex, delicate, and time-consuming problem [1].

System restoration after total blackout requires coordination of units, loads and transmission system, and the associated characteristics. Furthermore, various constraints imposed in generating restoration plans must be considered [2].

Nowadays, new technologies provide powerful new capabilities in areas such as large-scale system analysis, communication and control, data management, artificial intelligence, and allied disciplines. Planning of power system restoration is a combinational problem [2]. This issue also involves restrictions and conditions that make it more complicated for operators to judge rendering it. A system to provide answers to this issue with sufficient speed which is appropriate for practical applications has not been developed with such conventional techniques as optimization algorithms.

Quick restoration of power system after a blackout is a significant part of system operation. In the early stages of power system restoration, the black start units are of the greatest interest because they will produce power for the auxiliaries of the thermal units without black start capabilities. The black start units are usually those with combustion turbines or hydroelectric units [3–6].

Frequency is an important parameter in power systems, and accurate real-time measured frequency is highly desirable to understand the dynamics of power systems. Throughout the power system restoration, very large steps of power generators' loading are prone to result in frequency protection trips and consequently, prolong the whole process of power system restoration.

Operators are often concerned with the size of loading steps of power generators but nowadays, the introduction of Wide Area Measurement System (WAMS) which utilizes phasor measurement units (PMUs) leads to online power system monitoring and control. Several major utilities have shown an interest in the synchronous phasor measurement technology application. These include Hydro-Québec, American Electric Power, the New York Power Authority, Électricité de France (EDF), and many utilities of the Western Systems Coordinating Council (WSCC) such as Bonneville Power Administration (BPA) and Southern California Edison Company [7, 8].

Based on the constraints of WAMS operation, power system frequency control differs from those of the older generations of power system operation and control. The main tasks which can be fully accomplished through WAMS include early recognition of large and small signal instabilities and maximization of load restoration amount [9].

It is necessary to make the frequency control system during power system restoration be more effective, which requires the location and the magnitude of all generations and loads. During power system restoration, both generation and load profiles are constantly changing however the conventional approaches for frequency control and protection have only one set point for all scenarios. Offline power generators' loading optimization is a common practice for electric power utilities in order to prevent dangerous imbalance between load and generation and strong frequency deviations during power system restorations. Major drawback of conventional approaches for frequency control during power system restoration is that local protection devices do not have a system view, and, therefore, they are not able to take optimized and coordinated actions. Even in the case of frequency control and monitoring, in which the frequency itself is a system index, the actions are taken locally on predefined design rules. Carrying out improper actions during power system restoration, especially in the early stages, will prolong the overall process. Generators' loading is one of the most important parameters should be managed considering power system operational constraints, load characteristics, and so forth. Offline scheduling of generators' load pickup could not guarantee that the actions will not cause further problems.

A necessity exists to develop a frequency control and monitoring approach during power system restoration based on WAMS that can customize frequency control algorithms dynamically in response to any system condition. Proper coordination of power system

operation characteristics, especially WAMS characteristics encountering power system frequency control and monitoring, and power system restoration planning is the main objective of the paper.

This paper presents a systematic method for power system frequency monitoring and control during power system restoration based on WAMS. The presented approach which consists of detailed load modeling and power generators' loading optimization is to prevent dangerous imbalance between the load and generation and strong frequency deviations through power system restorations with a practically acceptable speed and accuracy. Compared with the conventional power system restoration approaches which utilize offline power generators' loading optimization, the presented approach optimizes the generators loading just based on the current state of power system which results in a safe, smooth, and quick restoration.

Utilization of WAMS provides the operation system prediction of a practically precise load and generation modeling; in order to achieve detailed load model, static load modeling approach is utilized. Power generators' modeling is also accomplished utilizing the single machine equivalent of the power system based on PMU measurements. Such a high degree of precision in load and power generation modeling could not be achieved without using WAMS.

Proper coordination of load and power generation models leads to a reasonable estimation of the active power imbalance and the steady-state frequency. Using the same model, the amount of load pickup or generation increase required to keep the frequency within the allowable ranges can be calculated. Power generators are studied based on the associated classical models. The generators' internal voltage, reactance and rotor phase angle are estimated using PMU measurements. The mechanical power, inertia constant, and damping constant can be obtained by a least square error fitting on swing equations of the multimachine system.

The proposed approach for frequency control and monitoring during the early stages of power system restoration considering WAMS approach consists of a couple of steps: preparation of the single machine equivalent model based on PMU measurements and estimation of the active power imbalance and predicting the steady-state frequency. The same approach can be successfully utilized to determine the amount of load pickup or generation increase required to maintain the frequency. The model is highly applicable to assess frequency deviations during power system restoration planning when there is not enough time to use detailed power system frequency control modeling.

The proposed approach for power system frequency monitoring and control during power system restoration assists power system operator during the restoration process. Since the restoration should be safe, smooth, and quick, such an approach should be able to quickly and precisely predict frequency oscillations and adjust generators' loading so that the operational risks be as minimum as possible. Within the early stages of power system restoration, in which there are a few online power generators, subsystems are prone to be unstable. Improper power system frequency monitoring and control, especially within such stages, will prolong the overall process of power system restoration.

Simulation results of the presented methodology on the 39 bus New England power system [10] clearly show the effectiveness and applicability of the proposed method. It is noteworthy that the results show that the presented approach has a completely accepted precision and an outstanding speed. Compared with the well-known power system modeling software packages, power system frequency prediction is accomplished with less than 0.05%

error. The outstanding speed of the presented approach along with the result precision will result in a great promotion in power system restoration methodologies.

The rest of the paper is organized as follows. Section 2 describes the concepts and basic formulation of frequency monitoring and control. Section 3 presents the result of power system parallel restoration planning based on WAMS capabilities for the New England 39 bus New England power system which is taken into account for further simulations. The proposed frequency monitoring and control approach and detailed load modeling approach are presented in Section 4. This Section also presents and discusses simulation results over the New England 39 bus New England power systems. The conclusion drawn from the study and also the road map for future works are provided in Sections 5 and 6, respectively.

2. The Problem of Frequency Monitoring and Control

Frequency stability is a major concern in the operation of power systems. Following severe disturbances, such as insertion of a load block or increase of mechanical power of a large generation station, the average system frequency will change. If the frequency drop is not arrested before the frequency reaches 47–48 Hz in a 50 Hz system, thermal units are tripped to avoid damage from prolonged under frequency operation and this worsens the situation [11]. In these situations, it may be necessary to disconnect loads to preserve system integrity. Typical threshold values are 48–48.5 Hz for a 50-Hz system [11].

It is known that the active power mismatch following the addition of mechanical power of a generator or insertion of a load step can be calculated from the initial rate of change of the frequency and the system inertia constant according to (2.1) [12]:

$$\Delta P = 2H_{\text{system}}\frac{d\omega}{dt}, \tag{2.1}$$

where ΔP, H_{system}, and ω are the active power mismatch, the system inertia constant which is the sum of all generators' inertia constants, and the per unit angular velocity, respectively.

It is known that the initial rate of frequency change is proportional to the power imbalance and it also depends on the electric power system inertia. Also, the values of the minimum frequency and the new steady-state frequency which are reached during the transient process of generator loading are proportional to the power imbalance and depend on the dynamic properties of power system equipment and loads.

The active power mismatch can be used as an indication for the amount of active load that should be restored in order to provide the frequency establishment above the target value, for example, 48.5 Hz, or the amount of power generation increase in order to provide the frequency establishment below the target value, for example, 53 Hz. It is noteworthy that power generators are usually equipped with protective relays or other types of protective devices to trip them off line if the frequency either exceeds 106% or drops below 97% [13].

The proposed approach for frequency control during power system restoration based on WAMS is based on frequency stability prediction; WAMS capabilities avoid the drawbacks of conventional approaches. Also, decision making about control actions in the proposed approach is based on online measurements through PMUs and WAMS instead of on conservative offline assumptions.

In order to maintain the frequency within given bounds, the single machine equivalent model which is derived online is utilized for power system frequency control and monitoring and also to calculate the necessary load pickup or generation increase amount in the early stages of power system restoration. It is noteworthy that the presented approach is completely applicable in the case of generation-rich situations where over-frequency occurs and control actions increase power system loading consequently as well as the cases of under frequency occurrence.

The system inertia constant may intensely change at different stages of power system restoration. The presented approach extracts the inertia constants of online generators from WAMS; the load's frequency and voltage sensitivities are estimated online, during the initial stages following a disturbance, and are included in the system model on which the frequency control and monitoring approach is based.

3. Power System Parallel Restoration Based on WAMS Constraints

Power system restoration is the procedure of restoring generators, transmission lines and loads in a minimum time without causing damages to power system equipment and customers. There are different strategies for restoration of a power system. A couple of these strategies is introduced in [1]; "build-down" strategy of reenergizing the network before resynchronizing generators, and "build-up" strategy of restoring separated parts, called islands, and then they will be mutually interconnected.

In many systems the latter, parallel restoration, is advantageous because of a remarkable reduction in restoration duration and blackout costs. The more the total number of islands rises, the shorter the net duration of power system restoration. This "build-up" strategy leads to a power system restoration process which leads to an observable restoration which satisfies the associated power system operation constraints. Also, based on the constraints of WAMS operation, each island must be fully observable. In this section, an introduction to island organization algorithm for power system restoration based on WAMS is presented.

Supporting minimum generation of the islands and making all the islands observable are the main constraints of island organization algorithm for power system restoration based on WAMS [14].

3.1. Supporting Minimum Generation of Islands

There must be sufficient active demand to support the minimum power generation at each island:

$$\forall \, \text{island} \; : \sum P_G^{\min} \leq \sum P_D, \tag{3.1}$$

in which $P_G^{\min}$ and P_D stand for the minimum power generation and demand at the whole islands, respectively.

3.2. Making All Islands Observable

The next constraint is that all islands should be observable:

$$A_j \times W_j \geq \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}_{k \times k}, \tag{3.2}$$

where A_j is the network connectivity matrix of island j; W_j is the binary variable vector for island j representing buses at which PMU is installed; finally, k is the number of island buses.

In order to illustrate the applicability of the proposed approach, which is presented in detail in the next section, the 39 bus New England power system is studied [10]. Since the contribution of this paper is not based on power system parallel restoration planning, parallel restoration planning will not be discussed in detail.

Black start generators are assumed to be located at buses 5, 7, 8, and 10; PMUs are located at buses 2, 6, 9, 12, 14, 17, 22, 23, 29, 32, 33, 34, and 37 as well. The problem of minimal PMU placement is figured out based on integer programming (IP) approach [14]. The main optimization problem is formulated as $\min \sum_{i=1}^{n} w_i$ in which the binary vector w_i represents that either a PMU is located at a bus or not. Based on such a formulation, observable buses, buses whose voltage and current phasor are known, can be analyzed based on three observability issues:

   (i) if a bus is directly connected to a PMU, all the voltage and current phasor are known;

   (ii) if a bus is connected to a voltage observable bus and there is a transmission line between these buses, the bus will be voltage observable;

   (iii) if a transmission line is located between a couple of voltage observable buses, the transmission line will be current observable.

Consideration of the constraint presented in (3.2) for all the buses of power system assures that all the power system buses are observable. Also n is the total number of the power system buses. This PMU placement problem is solved before the islands are organized. After PMU placement at the power system, which satisfies (3.1) and (3.2), islands can be organized. Each island should be observable and its associated demand should support the minimum power generation.

A schematic representation of the 39 bus New England power system at the early stages of restoration is shown in Figure 1. There are four islands considered as the initial state of the power system restoration which successfully satisfy the above mentioned power system parallel restoration planning constraints. In order to analyze the effectiveness of the proposed approach for frequency control during power system restoration based on WAMS, simulations are carried out over the island which is shown at the right-hand side of Figure 1 [14].
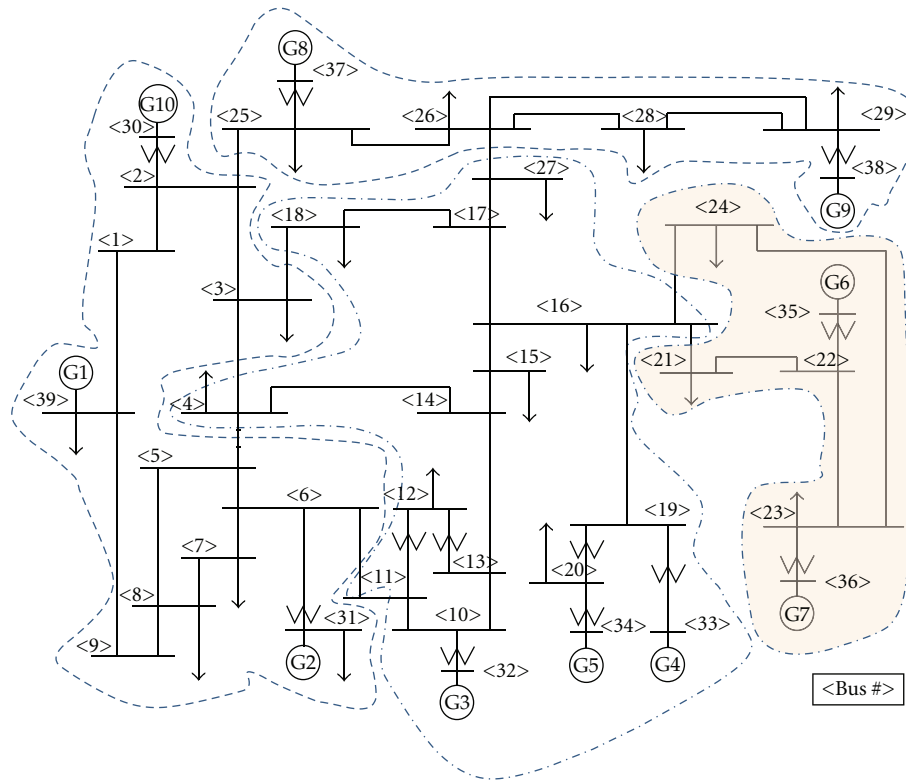
Figure 1: The islanded 39 bus New England power system at the early stages of restoration.

4. The Proposed Frequency Monitoring and Control Approach

Implementation of the proposed approach consists of a couple of steps. At first, the single machine equivalent model of each power system island is formed based on PMU measurements. At the next step, the model estimates the active power imbalance in the islands and also predicts the steady-state frequency. Using the same model, the amount of load pickup or generation increase, required to keep the frequency within allowable ranges can be calculated.

4.1. System Modeling

The proposed frequency monitoring and control approach is based on the single generator model of each power system island (i.e., the classical model [12]).

In the classical model, a synchronous generator may be modeled as a constant internal voltage source behind a reactance. The values of generators' internal voltage, reactance and rotor phase angle are estimated based on PMU measurements. The mechanical power, inertia constant, and damping constant can be obtained by a least square error fitting on swing equations of the multimachine system.

Detailed formulation of this parameter estimation process based on the least square method using continuous samples of PMU measurements is presented in [15] and it is not

repeated here. More details about estimation of synchronous generator parameters from online measurements will be found at [16, 17].

Based on the classical representation of synchronous generators, the associated active and reactive power can be presented as follows:

$$P = \frac{EV}{X} \sin(\delta), \qquad Q = \frac{V(E \cos(\delta) - V)}{X}. \tag{4.1}$$

Equation (4.1) is the basis of synchronous generators' parameter estimation. For each generator, a set of terminal voltage phasors and injected active and reactive powers are obtained from PMU measurements. Consider m set of measurements (including direct measurements and data drawn from power system state estimations) at the terminal of a generator; there are $2m$ nonlinear equations such as (4.1) in which P, Q, and V are known and there are $m + 2$ unknowns (E, X, and m values for δ). Considering the sampling rate of PMUs and the total duration of power system modeling, it is assumed that, for each generator, the whole m set of measurements are of the same internal voltage (E); the equivalent reactance (X) at the whole m set of measurements are also assumed to be the same.

Swing equation of each generator is presented in (4.2):

$$\frac{2H}{w_s} \frac{d^2\delta}{dt^2} = P_m - \frac{K_D}{w_s} \frac{d\delta}{dt} - P_e. \tag{4.2}$$

Unknown parameters in the swing equation are H, K_D, and P_m. These parameters should be estimated. Known parameters are w_s and P_e. Since the governor's actions are neglected, the mechanical power of the generator is assumed to be constant. P_e is the same as P presented in (4.1).

The frequency dynamics can be described using

$$\frac{d\omega}{dt} = \frac{1}{2H_{\text{system}}} (P_m - P_e), \tag{4.3}$$

where

$$H_{\text{system}} = \sum_{i=1}^{N} H_i,$$

$$P_m = \sum_{i=1}^{N} P_{m,i}, \tag{4.4}$$

$$P_e = P_{\text{loss}} + \sum_{i=1}^{M} P_{l,i}.$$

The constants N and M are the total number of generators and loads, respectively. H_i is the inertia constant of generator i; H_{system} is the system inertia constant. The mechanical power delivered to the shaft of generator i is denoted by $P_{m,i}$; the load consumed at bus i is denoted by $P_{l,i}$; the active power losses are denoted by P_{loss} and finally, the system average

frequency is denoted by ω; from the frequency stability control point of view, the average frequency has high importance.

Arriving at a high level of detailed load modeling, static load modeling approach is utilized [12]

$$P_{l,i} = P_{0,i}\left(\frac{V_i}{V_{0,i}}\right)^{\alpha_i}(1 + b_i(\omega - \omega_s)), \tag{4.5}$$

where $V_{0,i}$ is the nominal voltage; $P_{0,i}$ is the nominal load and ω_s is the power system synchronous frequency. Linearization of the load model and writing it on vector form yield

$$\Delta P_{l,i} = \left(P_{0,i}\frac{\alpha_i}{V_i}\left(\frac{V_i}{V_{0,i}}\right)^{\alpha_i}(1 + b_i(\omega - \omega_s))\right)\Delta V_i + \left(P_{0,i}\left(\frac{V_i}{V_{0,i}}\right)^{\alpha_i}b_i\right)\Delta\omega,$$
$$\Delta P_L = A\Delta V + B\Delta\omega, \tag{4.6}$$

where A is a diagonal matrix and B is a vector.

In order to consider the voltage variations' effects on the load points, the approach proposed by [12] is augmented with matrices of sensitivity coefficients

$$\Delta V = C\Delta P_L. \tag{4.7}$$

Combining (4.3) and (4.5)–(4.7) to eliminate the variables ΔV and P_L, the model can be restated as an ordinary differential equation (ODE).

$$\frac{d\Delta x}{dt} = A_{\text{ode}}\Delta x + B_{\text{ode}}\Delta d, \tag{4.8}$$

where x is the dynamical state vector and $\Delta x = x - x_0$. Also, x_0 is the value of the state vector at the linearization point. In this paper, the state vector just comprises the system average frequency and is thus a scalar. Δd represents a disturbance input (i.e., load pickup or generation increase).

The frequency derivative is approximated using the following approximation.

$$\dot{\omega}(t) \cong \frac{\omega(t) - \omega(t - k)}{k}, \tag{4.9}$$

where k is the sampling interval.

The parameters a_i and b_i in the load model (4.6) can be determined from measurements taken at (at least) three different samples and then the load parameters are estimated in a least squares manner. Once the load parameters have been determined, the system model could be derived as an ODE (4.8).

For the cases with no governor control, the steady-state frequency is equal to the minimum value. The online active power mismatch can be estimated utilizing (4.10).

$$\Delta d = 2H_{\text{system}}\dot{\omega}(t). \tag{4.10}$$

The total amount of active power imbalance will change due to load frequency and voltage sensitivity as well as applied control actions. Thus, it is just at the instant of disturbance that the active power mismatch is equal to the amount of increased generation or load. Using the estimated power mismatch (4.10), the predicted steady-state change in the state vector can be easily estimated utilizing the following equations. Consequently, the actual output will be known:

$$\Delta x^* = A_{\text{ode}}^{-1} B_{\text{ode}} \Delta d, \tag{4.11}$$

$$x^* = \Delta x^* + x_0. \tag{4.12}$$

4.2. Simulation Results

In this section, the accuracy and applicability of the proposed approach for frequency monitoring and control during power system parallel restoration planning is illustrated using a couple of cases. In both cases, as mentioned earlier, simulations are carried out over the island shown at the right-hand side of Figure 1.

Case 1. 20% increase in load at bus 24 is made at $t = 20$ sec. According to the 39 bus New England power system standard data, active power consumption of this load point is 308.6 MW. 20% increase in its power consumption equals 61.72 MW. In order to let the system frequency to reach the steady-state, the total simulation duration is considered 100 sec. Based on the results of proposed methodology, the steady-state frequency is 49.72 Hz, but well-known power system modeling software packages calculate it equal to 49.74 Hz as illustrated in Figure 2.

Case 2. 40% increase in generation at bus 36 is made at $t = 5$ sec. According to the 39 bus New England power system standard data, active power generation of unit G7 is 560 MW. 40% increase in its power generation equals 224 MW. In order to let the system frequency to reach the steady-state, the total simulation duration is considered 100 seconds. Based on the results of proposed methodology, the steady-state frequency is 50.44 Hz, but well-known power system modeling software packages calculate it equal to 50.42 Hz as illustrated in Figure 3.

Although there is about 0.05% error in the steady-state frequency calculation, but the major advantage of the proposed approach is rooted in its quick response and modeling simplicity.

Simulation results illustrate that the presented approach predicts the steady-state frequency after each loading action during the early stages of the power system restoration; compared with the results of using well-known power system modeling software packages, the presented approach succeeds to predict the frequency variations during the power system parallel restoration planning with less than 0.05% error.

Actually, the best application of the presented approach is to determine the best sequence of load pickup during power system restoration based on WAMS considering the hard constraints of power system operation in relation with frequency stability issues. Power system frequency should be kept in the allowable ranges of variations, for example, 48.5–53 Hz. This can be fully accomplished utilizing the fixed boundaries of power system frequency variations and repeating the process of calculations in a reverse manner. In other
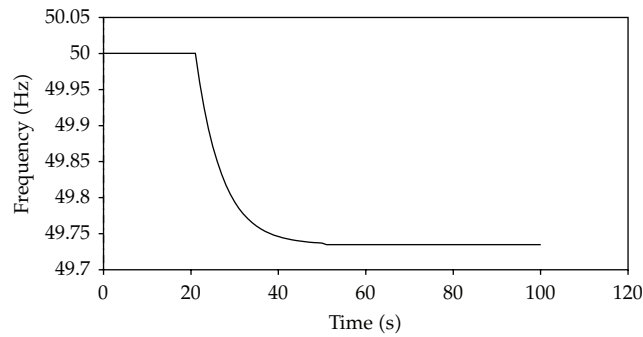
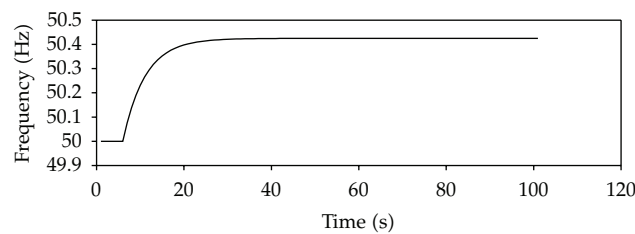**Figure 2:** Frequency variations after 20% increase in load at bus 24.

Figure 3: Frequency variations after 40% increase in generation at bus 23.

words, the generator loading sequence based on WAMS can be determined; in order to achieve such a model, the fixed boundaries of power system frequency variations will be represented as the model input, Δx, and also the load pickup or generation increase disturbance input will be represented as the model output, Δd. This reverse problem modeling will be addressed at the future works of the authors.

5. Conclusion

Frequency monitoring and control during power system restoration has not been addressed strongly yet. Operators are often concerned with the size of load and generation, which can be safely increased. But nowadays, the introduction of WAMS makes it possible to monitor the stability of power system online. Based on the benefits of WAMS operation, power system frequency control approaches are improved. A novel method for frequency control and monitoring during the early stages of power system restoration considering WAMS approach is presented which utilizes an accurate load modeling. The model is highly applicable to assess frequency deviations during the power system restoration planning when there is not enough time to use detailed power system frequency control modeling.

In order to achieve detailed load model, static load modeling approach is utilized. Power generators' modeling is also accomplished utilizing the single machine equivalent of the power system based on PMU measurements. Such a high degree of precision in load and power generation modeling could not be achieved without using WAMS.

Simulation results of the presented method on both cases of the 39 bus New England power system clearly show the effectiveness and applicability of the proposed method; load and generation increase are considered as disturbances which make power system frequency

faces strong variations which necessitate online frequency monitoring and control during power system restoration planning. It is noteworthy that the results show that the presented approach has a completely accepted precision and an outstanding speed. Compared with the well-known power system modeling software packages, power system frequency prediction is accomplished with less than 0.05% error. The outstanding speed of the presented approach along with the result precision will result in a great promotion in power system restoration methodologies.

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The best application of the presented approach is to determine the best sequence of load pickup during power system restoration based on WAMS considering the hard constraints of power system operation in relation with frequency stability issues.

6. Future Work

There is a variety of operational functions which their joint cooperation results in power systems restoration. Power system islanding at the first steps of power system restoration is one of such functions. This paper represents results of some phases of a research project which is to optimize power systems restoration based on recently presented technologies. Looking to the future, the presented approach will be modified in such a way that it can play the requested roles in a fully automated and comprehensive power systems restoration software package.

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