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Application of active power sensitivity to frequency and voltage variations on load shedding

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ABSTRACT

The occurrence of a large disturbance in a power system can lead to a decline in the system frequency and bus voltages due to a real and reactive power deficiency or due to the formation of islands with generation–load imbalance. Load shedding is an emergency control action that can prevent a blackout in the power system by relieving the overload in some parts of the system. This paper shows that rate of change of frequency can be utilized to determine the magnitude of generation–load imbalance, while the rate of change of voltage with respect to active power can be utilized to identify the sensitive bus for load shedding. The frequency, voltages and their rate of change can be obtained by means of measurements in real-time from various devices such as digital recorders or phasor measurement units or these parameters can be estimated from the voltage data by other means such as an optimal estimation method like Kalman filtering. The rate of change of system frequency, along with the equivalent system inertia may be used to estimate the magnitude of the disturbance prior to each load shedding step. The buses with a higher rate of change of voltage may be identified as the critical ones for load shedding and load can be first shed at these buses, depending on the change in the power flow at each bus. This application is tested on the IEEE 30 bus system and the preliminary results demonstrate that it is feasible to be used in load shedding to restore system voltage and frequency.

1. Introduction

Present day power systems transfer large amounts of energy over an extensive area and are being operated closer to the stability limit, thereby making them more vulnerable to disturbances. There are some areas rich in generation and some areas rich in load in these stresses systems, but their interconnection may be weak due to bottlenecks on the transmission network. Also generation reserves are minimal and reactive power is often in short supply where it is needed. A triggering event like a fault on an important facility can lead to a wide area disturbance and subsequently certain quantities such as voltage, frequency and power flows may leave the secure range. Load shedding is one of the most effective measures for averting a power system blackout. When the power system is approaching a catastrophic failure, shedding some amount of load at certain locations relieves the overload on the system, limits the extent of the disturbance and helps in retaining power supply to the important loads. The main objectives of this paper are: (i) to test the application of frequency variation to estimate the generation/load imbalance; (ii) to test the application of voltage variation in identifying appropriate locations for load shedding.

Various types of load shedding schemes have been formulated and implemented by utilities in the past. Most of the earlier schemes were traditional schemes that relied heavily on local measurements for inputs and shed a preset amount of load when frequency or voltages reached a certain level. The traditional schemes were later replaced by semi-adaptive and adaptive under frequency load shedding schemes [1–8] that tried to overcome the problem of under shedding or over shedding of load by utilizing the rate of change of frequency along with the frequency value to make decisions about shedding load. Under voltage load shedding schemes [9–21] started making an appearance a few years ago as they proved to be an economical and effective technique to maintain voltage stability as against expensive and time consuming methods like shunt compensation, new additions to the main circuit, etc. With the advent of advanced metering and communication systems, centralized load shedding schemes [22] that used frequency and voltage values from different parts of the system as inputs became widespread. Some load shedding schemes were based on optimization procedures [23–26] that aimed at reducing

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the cost incurred due to load shedding while others used neural networks and fuzzy logic [27–29] as an aid for determining the amount and location of load shedding. It can be observed though that the limitation of most of these schemes is that they focus mainly on just one parameter: frequency or voltage, whereas in case of many contingencies both the parameters may be affected simultaneously and should be considered. Also some schemes relied on just the level of frequency or voltage and ignored the rate of change of these parameters. The rate of change of frequency and voltages are instantaneous indicators of power deficiency and enable incipient recognition of disturbances. Hence a load shedding scheme that uses frequency, voltage and their rate of change as inputs and determines amount of load to be shed and location of load shedding is proposed in this paper with an aim of shedding the minimum amount of load and restoring normal system conditions in a short period of time. In summary, available load shedding schemes are either based on frequency change or voltage changes. This paper presents a unique load shedding scheme that combines frequency, voltage, rate of change of frequency and rate of change of voltage to shed an optimal amount of load at suitable locations.

This paper is organized as follows: Section 2 gives an overview of the various measurement techniques for frequency and voltages. Section 3 describes the relation between rate of change of frequency and the power mismatch and the utilization of rate of change of voltage for identifying appropriate bus for load shedding. The testing of the scheme is presented in Section 4 and Section 5 summarizes the conclusions and future work.

2. Frequency and voltage measurement techniques

The frequency, voltages and their rate of change are the inputs to the application of active power sensitivity to frequency and voltage variation on load shedding and they can be measured by devices such as meters, relays, phasor measurement units (PMUs) and digital recorders. Wide area measurements using PMUs [30] are the most advanced form of monitoring as they are synchronized by a Global Positioning Satellite (GPS) system to the order of 1 μs and this time stamped data gives the operator in the control room a coherent and dynamic view of the network. Synchrophasor measurement capabilities have been available as stand alone units (PMU). Subsequently, relay manufacturers introduced synchrophasors into microprocessor-based relays as a standard capability [31–35]. Synchrophasors data rates are scalable from once a cycle to once a second. These synchrophasors devices such as relays are already in power systems at critical measurement points that can be used in this application. These synchrophasor measurements would be the preferred source for an application as dynamic and time sensitive as the load shedding.

However in the absence of these sophisticated devices, the required inputs may be estimated by other means. Frequency can be estimated from the voltage waveforms by different methods [36,37] such as Fourier analysis, Prony analysis, Newton's iteration, Taylor approximation, etc. One of the optimal estimation techniques that may be used for obtaining frequency, voltages and their rate of change from the recorded voltage data is a two-stage Kalman filter [37]. The Kalman filter is used in this paper for estimation purposes as it takes in to account the measurement noise and the process noise in the voltage for optimal estimation. The first stage of this technique is an extended Kalman filter that estimates the frequency, voltage magnitude and phase angle from the voltage data and the next stage is a linear Kalman filter that estimates the rate of change of frequency and rate of change of voltage from the frequency and voltages, respectively.

3. Active power sensitivity to frequency and voltage variations

The main goals of this paper are: (i) to use the rate of change of frequency to accurately estimate the generation–load imbalance that will identify the amount of load to be shed and (ii) to use the voltage variation to identify the appropriate buses for load shedding.

The most basic equation of motion [38] for a machine is given by

$$J.\frac{d\omega_m}{dt} = T_a = T_m - T_e \tag{1}$$

where, J is the moment of inertia of the generator and turbine in kg m^2, ω_m is the rotor mechanical angular velocity in rad/s, T_a is the accelerating torque in Nm, T_m is the mechanical torque in Nm and T_e is the electrical torque in Nm. T_m and T_e are equal during normal system operation and hence the machines do not accelerate or decelerate. The inertia constant which is commonly used in stability studies is defined as

$$H_i = \frac{W_{Ki}}{\text{system base MVA}} \tag{2}$$

where H_i is the inertia constant for machine i in seconds, W_{Ki} is the total kinetic energy of the generator and turbine at bus i in MWs, and this is divided by the three-phase system MVA base.

Thus, the equivalent inertia constant H for the entire system can be determined as

$$H = \sum_{i=1}^{N} H_i \tag{3}$$

where the summation is done for all the on line generators.

Substituting H in place of J in (1), having the torque and power in per unit form and considering the fact that ω is nearly equal to one per unit,

$$\frac{2H}{\omega_0}\frac{d\omega}{dt} = T_m - T_e = P_m - P_e \tag{4}$$

where ω_0 is the rated speed of the machine in rad/s, T_m is the mechanical torque in per unit, T_e is the electrical torque in per unit, P_m is the mechanical power in per unit and P_e is the electrical power in per unit. But $\omega = 2\Pi f$ and hence if f_0 is the rated frequency in Hz, df/dt is the rate of change of frequency in Hz/s and P_{dist} is the power imbalance or the magnitude of the disturbance in per unit then

$$\frac{2H}{f_0}\frac{df}{dt} = P_{dist} \tag{5}$$

A negative value of df/dt gives a negative value of P_{dist}, which implies that the electrical power as seen by the machines in the system is greater than the mechanical power that is being input to them by the prime mover, or in other words there is an overload in the system. Thus P_{dist} is the generation–load imbalance and signifies the magnitude of the disturbance. Eq. (5) may be used to estimate the magnitude of disturbances (generation–load imbalance) using the equivalent inertia constant and the instantaneous rate of change of frequency. The disturbance magnitude is the amount of load to shed at that particular load shedding step. The next task is to identify the appropriate buses for load shedding.

Buses may be ranked according to the rate of change of voltage. The buses with the steepest rate of voltage decline can be selected first as appropriate buses for possible load shedding. It is also checked if there is sufficient load at the critical buses to be dropped at that step. The load to be shed is divided among the critical buses depending on their sensitivity of change in injected power to the change in voltage as,

$$\Delta P_i = \frac{(dP_i/dV_i).\Delta V_i}{\sum[(dP_i/dV_i).\Delta V_i]} \times P_{\text{dist}} \quad (6)$$

where ΔP_i is the real power load to be shed at bus i, ΔV_i is the voltage drop at bus i, P_{dist} is the total amount of load to be shed at that step and the summation is done over the critical buses that have been selected for load shedding.

The real power injected in to a bus is given by

$$P_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \ \cos(\delta_i - \delta_j - \theta_{ij}) \quad (7)$$

$$\frac{dP_i}{dV_i} = \sum_{j=1}^{n} V_j Y_{ij} \ \cos(\delta_i - \delta_j - \theta_{ij}) \quad (8)$$

where P_i is the real power injected in to bus i, V_i and V_j are the instantaneous voltage magnitudes at bus i and bus j in per unit, Y_{ij} is the admittance magnitude of the line connecting buses i and j, δ_i and δ_j are the instantaneous voltage phase angles in radians at bus i and bus j and θ_{ij} is the angle of admittance Y_{ij}. The instantaneous values of voltage magnitudes and phase angles at each load shedding step, as obtained form the Kalman filter, are considered in this calculation, the elements of the admittance matrix being the same as the one at steady state (unless any line switching has taken place). A proportional amount of reactive power ΔQ_i also gets dropped when we lose real power load ΔP_i at any bus, say bus i and it is given by

$$\Delta Q_i = \Delta P_i \times \tan(\cos^{-1}(\text{power factor at bus } i)) \quad (9)$$

The time interval between load shedding steps can be adjusted to the shortest possible interval as desired to account for the delays in measurement, time taken for online computation of the load shedding amount and the delay in sending control signals to breakers on feeders to open and shed load. It is practical though to maintain a time step of at least 0.1 s between subsequent load shedding steps. The frequency and voltages are monitored after shedding load at each step and the load shedding scheme continues as long as the frequency and voltage cross the set threshold.

4. Testing the proposed application

The IEEE 30 bus system has been used for testing the proposed algorithm. The test system has 6 generators, 41 lines and about 190 MW load. The test system is modeled in PSCAD/EMTDC for the purpose of simulation to evaluate this application on load shedding. Detailed generator models that have turbines, exciters, governors and stabilizers are used for modeling the machines. The lines are represented by coupled pi models and the loads are assumed to be constant MVA, constant power factor loads. The loads are modeled using the most pessimistic model viz. constant MVA model and hence they continue to consume the same amount of power irrespective of the frequency and voltage decline after the disturbance thereby deepening the gap between the generation and load. A power flow program such as the Newton Raphson technique is run for the test system in Matlab to obtain the initial values of voltage phase angles at the generator buses as these are needed for modeling in PSCAD. The voltage data is available from PSCAD/EMTDC at a rate of 16 samples per cycle and it is passed through a two-stage Kalman filter to estimate the frequency, voltage and their rate of change. A disturbance is simulated in the system as the loss of the generator producing 60MW at $t = 0$, which causes a real and reactive power deficiency in the system.

In the absence of any control action such as load shedding, it can be seen from Figs. 1 and 2 that both frequency and voltage start declining after the disturbance occurs. There is a rise in the voltage at about $t = 3$ s due to the initialization of exciter action on the generators. The rate of change of frequency also becomes less steep at nearly $t = 6$ s due to the governor action on the remaining machines. However, the reserves in the system are inadequate and the frequency and voltage continue to stay at an unacceptably low value even after the exciters and governors of the remaining machines in the system have played their role in attempting to restore normal conditions.

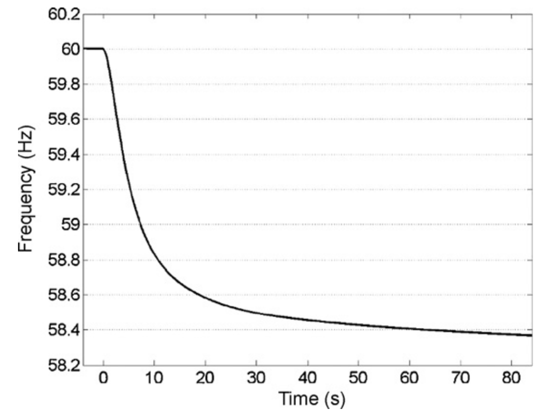

Fig. 1. Average system frequency without load shedding.

Now, load shedding is applied based on the described principles after the occurrence of a disturbance. The voltages cross the threshold of 0.97 per unit in less than a second after the disturbance occurs and this initiates load shedding. The instant of time at which the disturbance occurs is considered as $t = 0$ and the load shedding scheme starts after $t = 0$. The total amount of load shed is 60.7 MW at various buses in the system based on their rate of change of voltage. The actual amount of load shed is rounded off to the nearest number corresponding to the disturbance magnitude at that step as the load at each bus is assumed to consist of an aggregation of several feeders of varying capacities and the breaker for the feeder carrying the load closest to that calculated is opened. The frequency estimation and load shedding computations are done in Matlab. All loads in the system are considered to be constant power factor loads and hence a proportionate amount of reactive power is also shed along with the real power.

Figs. 3 and 4 show the frequency and voltages on implementing the load shedding scheme. It can be observed that the lowest value that the frequency reaches now is 59.66 Hz as against the low of 58.4 Hz that it reached without any load shedding after the disturbance. The frequency reaches an acceptable value of 59.95 Hz

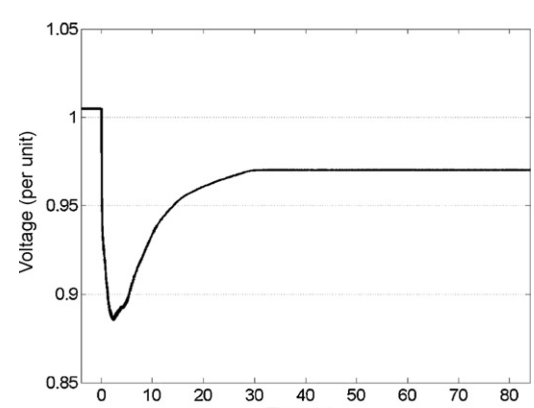

Fig. 2. Average voltage at buses close to the disturbance without load shedding.

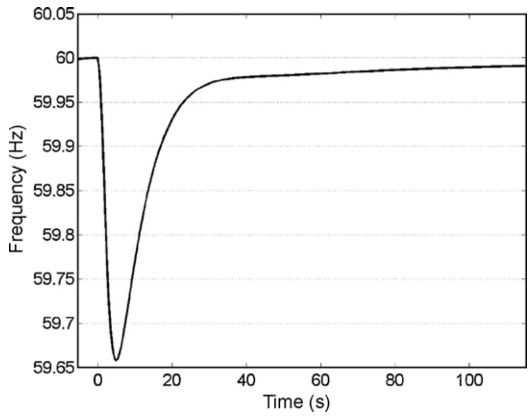

Fig. 3. Average system frequency on implementing the load shedding scheme.

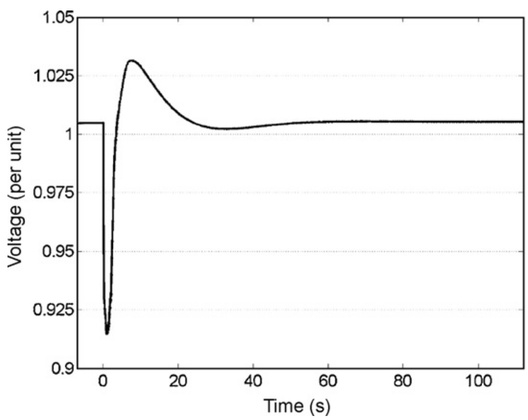

Fig. 4. Average voltage at buses close to the disturbance on implementing the load shedding scheme.

in 25 s and settles down to a nearly nominal value of 59.99 Hz in about 120 s after the disturbance occurs. The voltage profile also shows a tremendous improvement. The lowest value of voltage is now 0.915 per unit as against 0.88 per unit without load shedding. The voltage returns nearly to a nominal value in just 5 s and settles down to a final value of 1 per unit in about 30 s.

Thus, as seen from the results, the load shedding scheme restores the frequency and voltages to their nominal values in a very short time period.

5. Conclusion

The preliminary results of load shedding based on the described principles show that: (i) the rate of change of frequency can estimate the magnitude of the disturbance accurately and (ii) the rate of change of voltage with respect to active power can identify the location for load shedding and provide a weighting factor for the amount of load to be shed at each bus.

The future work on this scheme would involve using realistic load models in order to observe the effect of the load characteristics on the system state. The market price as well as priority listing for loads could be included in the scheme to minimize the economic losses incurred due to load shedding and to avoid shedding high priority loads. The inter area energy transfers can also be considered in the scheme as these will affect the amount of load to be shed. The possibility of having a multiple contingency in the system due to cascading can also be investigated as regards its effect on the system and to test the effectiveness of the load shedding scheme in such a situation. The scheme may be tested on a bigger system in order to check its efficacy. Thus, the load shedding scheme that has been developed will provide a good starting point for further analysis in this field.

Appendix A. List of symbols

J	moment of inertia of the generator and turbine
ω_{m}	rotor mechanical angular velocity
T_{a}	accelerating torque
T_{m}	mechanical torque
T_{e}	electrical torque
H_i	inertia constant for machine i
W_{Ki}	total kinetic energy of the generator and turbine at bus i
ω_0	rated speed of the machine
P_{m}	mechanical power
P_{e}	electrical power
f_0	rated frequency
df/dt	rate of change of frequency
Y_{ij}	admittance of line between buses i and j
P_i	real power injection at bus i
V_i	voltage at bus i
V_j	voltage at bus j
δ_i	voltage phase angle at bus i
δ_j	voltage phase angle at bus j
θ_{ij}	difference in voltage angles between buses i and j
P_{dist}	power imbalance or magnitude of the disturbance in per unit
ΔP_i	real power load shed at bus i
ΔQ_i	reactive power load shed at bus i
ΔV_i	voltage drop at bus i

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