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Transients Instability Detection and Prevention Control Schemes

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Effective real time monitoring and analysis of power system has become very important from the point of view of power system stability and security. Recent research in literature has identified that it is possible to determine the critical group of generators and hence predict the generators going out of synchronism. However, a clear mitigation scheme from a wide area perspective has not yet been identified. The main contribution of this paper deals with the post prediction of instability phase. After the identification of the critical generator or group of generators, effective actions such as load shedding should be initiated. The work targets in finding the optimal location where load is to be shed using the rotor angle algorithm and the Jacobian based distribution factor sensitivity

Keywords: *Transient Instability Prediction, Wide Area Measurements, Synchrophasor, Rotor angle algorithm, Load shedding.*

1.0 INTRODUCTION

The reliability of power system is a hot topic of research. With the day to day increasing power demand and the generation trying to meet up the load, maintaining power system reliability and stability are some of the serious issues in today's world. The system being complex, any fault condition or instability will result in huge losses to the generation and distribution sector. The August 2003 blackout in North Eastern United States and Canada cost 6 billion USD in revenue alone. Hence, the effective real time monitoring and analysis of power system has become very important.

State estimation was one of the most powerful conventional tools for identification of instability. But, with the advent of synchrophasors, the state of the system is directly measurable in real time. Hence, the prediction of transient instability based on the system characteristics in real time has become easy.

Whenever a fault happen in power-grid, by the analysis of the response characteristics we can provide warnings before the transient stability is lost.

Whenever there is a fault or transient instability, all the quantities except Pm (Mechanical power input) change. Hence, there will be an unbalance between the electrical and mechanical torque. This either leads to speeding up or slowing down of generator. Hence, there will be a nonlinear variation in the rotor angle. By monitoring this rotor angle variation, we will be able to monitor the stability of the system.

The prediction methods can be broadly divided into two.

1. Perturbed rotor angle trajectory prediction. [1][2][3][4][5][6]
2. Methods based on real time wide areaphasor measurements. [7][8][9][10]
3. Methods based on intelligence algorithm. [11][12][13][14][15]

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The increased use of synchrophasor and the data availability have narrowed the computational complications linked with the rotor angle monitoring. In this study, we assume that the synchrophasors are electrically located near to the generators so that the bus angle at the generator stations can be approximated to rotor angle. [10] A 39 New England bus system is considered for the study. The study can be divided into three phases:

i. Prediction/Monitoring of fault

ii. Identification of critical generators/loads.

iii. Identification of the optimal bus and amount of load/generation to be shed.

2.0 EXISTING LITERATURE

2.1 Perturbed rotor angle trajectory prediction

Curve fitting is the key tool in perturbed rotor angle trajectory prediction method. The main advantage of this method is that it doesn't need any network equivalence or other model parameters for prediction. The short time post fault rotor angle measurements are taken and trajectory extrapolation is done ignoring the non-linearity. The existing perturbed rotor angle trajectory prediction can again be divided into three.

1. Based on network dynamic equivalence
2. Based on trajectory extrapolation
3. Based on angular velocity prediction and integration

2.2 Prediction based on network dynamic equivalence

This is based on the principle that the outcome of an evolving swing can be predicted in real time more accurately with the help of simplified dynamic models and by initiating an appropriate protection such as shedding of loads/ generations. Two piecewise dynamic equivalents was proposed in [2] which can replace the DAE with the local ordinary differential equation. As a result, the equivalent system can be integrated using the most recent data from the phasor measurements to obtain consistently accurate prediction to half of a second.

2.3 Prediction based on trajectory extrapolation

In this method, the rotor angle and angular velocity are expressed as polynomial functions or trigonometric functions and this has the advantage of needing the minimum amount of data.

The three models used for rotor angle are polynomial function model, trigonometric functionmodel and auto regressive function model.

Polynomial function model [3] is based on the truncated Taylor series expansion and accordingto that rotor angle can be represented by the equation

$$\delta(t) = a_0 + a_1 t + a_2 t^2 + \ldots + a_n t^n \quad \text{....(1)}$$

Where,

$\delta(t)$ is the predicted value of rotor angle at time t.

n is the order of the model.

$AN = [a_0; a_1; a_2; \ldots a_n]^T$ can be solved by least square method.

Once the parameter vector is estimated, the lth step prediction can be found out by

$$\delta(k\Delta t) = a_0 + a_1 k\Delta t + \ldots. + a_n(k\Delta t)^n \quad \text{....(2)}$$

Where,

$k = N + 1, N + 2\ldots..N + l$

The parameter vector A is updated as the new measurements are obtained.

The trigonometric function model [4] is represented by the below equation. The parametersare estimated by the least square method as the polynomial function model.

$$\delta(t) = \sum_{t=0}^{\infty} a_n \cos nt + b_n \sin nt \quad ....(3)$$

2.4 Methods based on real time wide area phasor measurement

Transient instability can be predicted using the phasor measurement units based on two algorithms. Rotor angle algorithm [7] and Vmag algorithm [8] introduces an online voltage stability index that predicts power system voltage stability limit. This method simplifies the large networks into a single source and single transmission line, using network parameters and PMU measurements. It determines the voltage stability for all load buses and is simple to be applied in real time.

Computation of transient energy function using real time data from synchrophasors is another powerful method for predicting transient instabilities. Transient energy functions are formed by calculating the total energy of the individual or total generation as a function of rotor frequency and rotor angle displacement with an assumption that the total energy dissipated is negligible. The kinetic energy is a function of rotor frequency and potential energy is a function of rotor angle displacement. Thus, total energy is a function of quantities that can be measured by synchrophasors. Therefore, approximate total energy can be computed almost as quickly as the data becomes available. By studying the total energy of each machine, we can see how much energy each machine can produce or absorb from the system before losing synchronism with the grid. With energy function analysis, it is possible to compute the swing energy associated with the system disturbances during an event. The transient energy function can be computed as below.

$$TE_i = \frac{1}{2} M_i \omega^2 - \int_{\delta_1}^{\delta_2} (P_{mi} - P_{ei}) d\delta_i \quad ....(4)$$

Where,

Mi is the moment of inertia of ith generator,

Pmi is the mechanical torque of ith generator,

Pei is the electrical torque of ith generator,

δi is the rotor angle of ith generator.

By looking at the rotor angle alone we can determine the generators which are losing synchronism with the system. [9] The algorithm works by taking the estimated rotor angle and comparing with a set threshold. Once the threshold is exceeded, the rotor angle is integrated and if the integral exceeds a set amount before the rotor angle begins decreasing, then, control action is taken. In this algorithm the assumption is that the bus voltage angle obtained from the synchrophasor measurement is approximately equal to rotor angle. This is made on the premise that the bus is located electrically near the generator or the only impedance between the bus and the internal voltage is the synchronous reactance.

On simulation, the difference that this assumption brings in is about 1 to 20 degrees. But this is made irrelevant by referring the bus voltage on a centre of inertia frame. Phase angle can varyin wide range during system operation

2.4.1 Centre of angle

Centre of angle (COA) can be defined as

$$\delta_{COA} = \frac{\sum_{i=1}^{N} \delta_i H_i}{\sum_{i=1}^{N} H_i} \quad ....(5)$$

Where,

δ_i is internal machine angle

H_i is generator inertia constant

Since we can't measure directly the values of Hi we substitute its weight by the active power injections of the generator. Thus the centre of inertia angle reference for the area i, say, δ^i_c is

$$\delta_c^i = \frac{\sum_{j=1}^{N} \delta_j^i P_j^i}{\sum_{j=1}^{N} P_j^i} \quad ....(6)$$

By increasing the number of phase angle measurements within each area, we can increase the accuracy of computation of δ^i_c and improve redundancy.

Centre of inertia angle for reference for the entire system is written as

$$\delta_c = \frac{\sum_{i=1}^{N} \delta_c^i P^i}{\sum_{i=1}^{N} P^i} \quad ....(7)$$

Where,

N is the total number of areas that are available in the control formulation.

Pi denotes the current total generation in area i.

When δ_c^i in area i is continuously increasing away from the centre of inertia angle of the entire system beyond a specific limit it implies that area i is moving towards separation from the rest of the system. So, we should initiate tripping of generation.

When δ_c^i in area i is continuously decreasing, then also the area is separating from the entire system. Here we should initiate load shedding.

The thresholds are based on the ratio of the spinning reserve to total generation at any bus.

The lower the ratio, the lesser the threshold. The difference between the times of occurrence of the fault and the control action taken determines the severity of the disturbance. For severe disturbances both load shedding and generation shedding should be initiated. Determination of the optimal amount and buses of shedding of load or generation is the objective of the study.

2.5 Artificial intelligence based transient instability prediction

Artificial neural network based transient instability prediction is very promising because of the high precision, adaptability and flexibility to changing operating conditions and disturbances.

In [11] and [12] a class of fuzzy hyperrectangular composite neural networks which utilize synchronized phasor measurements to provide fast transient stability swings prediction is described. This method yields highly successful prediction rate in real time. [13] A radial basis function network based on fuzzy clustering and its learning algorithm is proposed in [14]. The

post fault rotor angles measured by PMUs are the inputs and it is used to predict the stability of multi machine power system. The perturbed trajectory based learning algorithm is proposed in [15]

One of the main disadvantages of artificial intelligence based transient instability prediction is that it takes large number of offline simulations for the learning process. Then, the validity of the prediction model has to be tested by using the non-sample set. Though the learningis conducted in a systematic way, there will still be mismatches between the real operating conditions and simulation conditions.

3.0 PROPOSED WORK

This study compares the energy function algorithm with the rotor angle algorithm, identifies the best algorithm and modifies it so as to be used with the identification of critical group of generators. The main contribution of this paper is the novel scheme for load shedding. The case study is made with a 39 bus New England system. The simulation results and conclusions are also formulated at the end.

The block diagram of the work is as shown in Figure 1. Compared to the conventional schemes, the difference in the proposed scheme is the identification of optimal bus and the distributive calculation of the amount of load to be shed.

3.1 Critical bus

A critical bus is the bus which is most sensitive to any disturbance and can result in instability of whole system or network splitting. Identification of critical bus and responding to the disturbance before any instability is been caused is the single most aim of protection devices. This study used the rotor angle algorithm to predict the critical generator which may go out of synchronism.

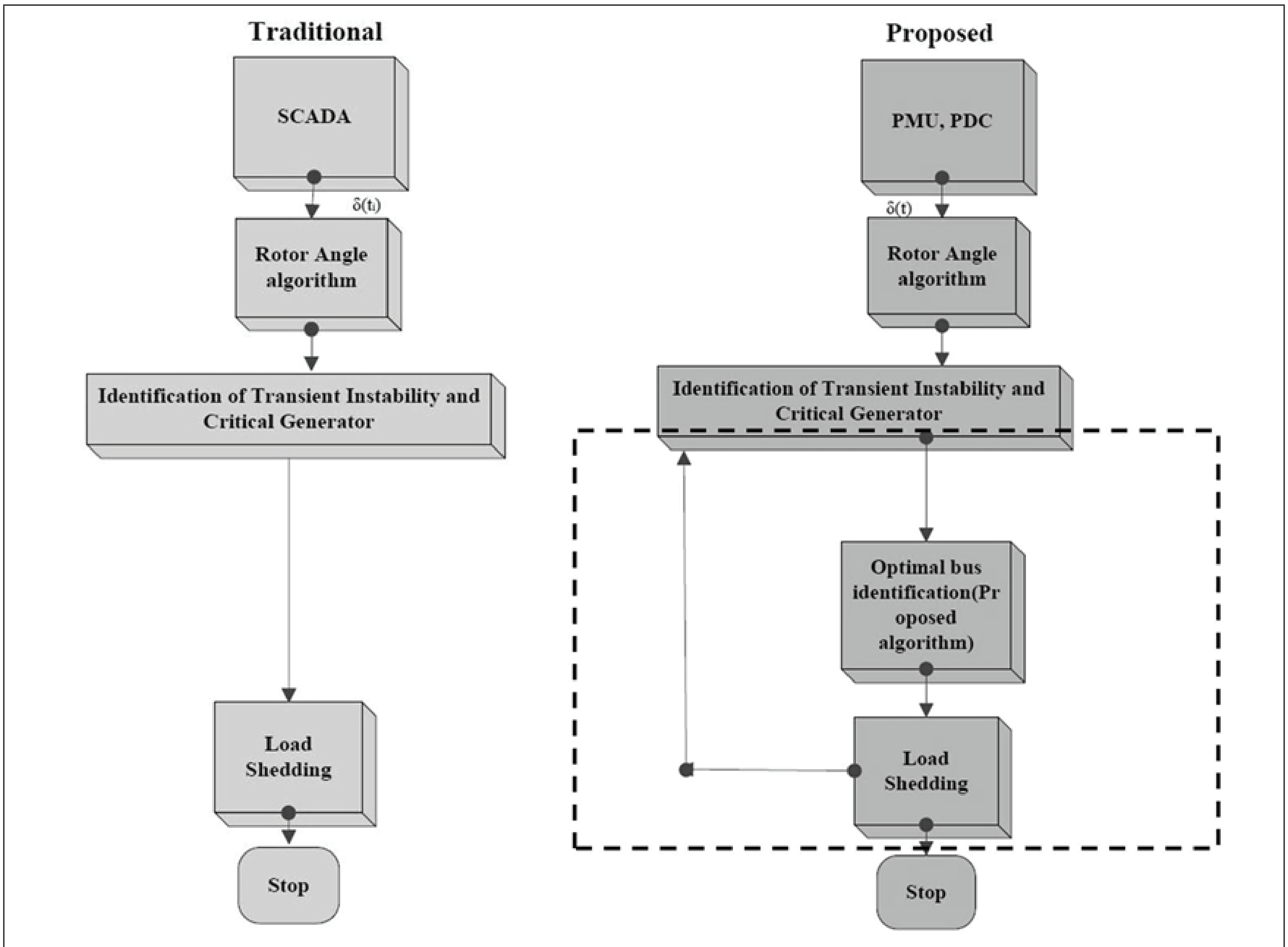

FIG. 1 COMPARISON OF PROPOSED WORK WITH TRADITIONAL METHODS

By the algorithm, critical bus is that bus which has $|\Delta\delta i| > \Delta\delta$ threshold. The threshold values are calculated by offline simulations. Finding the critical generator is the first step of theprediction algorithm

3.2 Optimal bus

A new phrase 'optimal bus' is coined in this work. This comes into picture after the identification of critical bus. An optimal bus is a bus which has the maximum effect on the stability of the critical bus. It can be one bus or a number of buses. The main difference of the conventional stability problem approach from this approach is that, here for instability in one generator bus, we don't blindly shed loads in the same bus. But we identify some of the surrounding buses where load shedding is possible maintaining the stability of the critical bus.

The algorithm used for identifying optimal bus is based on the sensitivity factors discussed in literature [16]. The Jacobian based distribution factor is used in real time to identify most sensitive load. The main advantage of this method is that it reflects both real and reactive powers.

Consider the power flow between bus i and k. Let that power be P_{ik}.

$$P_{ik} = G_{ik}|V_i^2| - G_{ik}|V_i||V_k|\cos(\delta_{ik}) - B_{ik}||V_i||V_k|\sin(\delta_{ik}) \quad ....(8)$$

For the analysis the line flows are modeled as,

$$P_{ik} = P_{ik}^0 + \sum_{j=1}^{N} F_{ik}(i,k,j)\Delta P_j + K_{ik}(i,k,j)\Delta P_j \quad ....(9)$$

Where,

$$F_{ik}(i,k,j) = \sum_{j=1}^{N} \frac{\partial P_{ik}}{\partial P_j}$$

$$F_{ik}(i,k,j) = \sum_{j=1}^{N} \frac{\partial P_{ik}}{\partial Q_j} \quad ....(10)$$

Accommodating the voltage magnitudes and phase angles and considering P_{ik} is related to only V_i, V_k, δ_i, δ_k

$$F_{ik}(i,k,j) = \frac{\partial |V_i|}{\partial P_j}\frac{\partial P_{ik}}{\partial |V_i|} + \frac{\partial |V_k|}{\partial P_j}\frac{\partial P_{ik}}{\partial |V_k|} + \frac{\partial \delta_i}{\partial P_j}\frac{\partial P_{ik}}{\partial \delta_i} + \frac{\partial \delta_k}{\partial P_j}\frac{\partial P_{ik}}{\partial \delta_k} \quad ....(11)$$

Now differentiate equation (10) to obtain the values for $\frac{\partial P_{ik}}{\partial |V_i|}, \frac{\partial P_{ik}}{\partial |V_k|}, \frac{\partial P_{ik}}{\partial \delta_i}, \frac{\partial P_{ik}}{\partial \delta_k}$

Similarly for K_{ik} (i,k,j).

Different sensitivity factors are calculated at different operating conditions and used for identifying the most sensitive load. The algorithm is applied to 9-Bus Anderson system and the results are as shown.

4.0 ALGORITHM AND SIMULATION

The sensitivity factor method is tested on a 9 bus Anderson system. The code was written and executed in MATLAB and the execution time was found to be around 15 ms in Windows Intel duo core processor where as that of the normal N-R method is 83ms.

The Jacobian based distribution factors are calculated on every loop of the load shedding algorithm to identify the optimal bus of load shedding. The values are shown in Table 1. The load shedding algorithm is explained with details in section 4.1.

TABLE 1

JACOBIAN BASED DISTRIBUTION FACTOR METHOD APPLIED ON 9 BUS ANDERSON SYSTEM

Line flows Between lines	**Line flows by**		**% Error**
	Load flow results	**Sensitivity factor method**	
1-4	71.64102	71.57	0.099135
4-6	19.28	19.32	-0.207469
4-5	52.37	51.78	1.126599
5-7	-66.3	-65.97	0.497738
6-9	-78.83	-78.1	0.926043
7-8	96.7	95.756	0.976215
8-9	-6.17	-6.67	-8.103728
9-3	-85	-84.97	0.035294
7-2	-163	-162.88	0.074847

The Algorithm for Load Shedding is given below

Algorithm:

Step 1: Get the δ_i measurements from PMU and compute $\Delta\delta_i$ w.r to threshold values

Step 2: If the threshold is exceeded go to step 3. Else step 1.

Step 3: Identify the critical bus. Obtain the JBDF with the generation loss at critical generator.

Step 4: Shed load at the most sensitive bus identified by JBDF

Step 5: Go to step 2.

4.1. Case study of WSCC system

The algorithm is applied to 9 bus test case. A three phase to ground fault is simulated between line 4-5 and the system goes out of stability. The results are as tabulated below in Table 2.

TABLE 2

CASE STUDY

Fault lines	**Critical generator**	**Optimal bus**
7-8	3,2	8

The main advantages and disadvantages of the existing system are as tabulated in Table 3.

TABLE 3

COMPARISON OF PROPOSED AND CONVENTIONAL SCHEMES OF TRANSIENT INSTABILITY DETECTION

Method	Advantages	Disadvantages
Conventional	Less complication in algorithm	Less reliability
Proposed	Load shedding is distributive	Load shedding in steps may cause inter-area oscillations and hence we have to initiate frequency control schemes.

5.0 CONCLUSIONS AND DISCUSSIONS

The optimal bus identification is carried out using the proposed algorithm and the load is being shed distributive. This is an important advantage of this method and has several benefits over tradition methods.

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