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Out-of-step Prediction for Power System Using Improved Prony Algorithm

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Abstract. The development of the phasor measurement units (PMUs) and the wide-area measurement systems (WAMS) in power system provide abundant synchronous data for the new application. This paper proposes an online out-of-step monitoring and predicting scheme for the interconnected power systems based on the rotor angle measurement. The Prony algorithm is improved to predict whether and when a power swing will lead to out-of-step of the generator or the power systems. An energy-like weight coefficient approximation of the decomposed signals is introduced to maintain the accuracy and reliability of the model free dynamic prediction method. The effectiveness and applicability of the proposed scheme is illustrated using a 2-area-4-machine power system.

1 Introduction

The angle stability is essential for the security of both generators and the whole power system. Despite the development of the protection and control of power systems, blackouts still happened from time to time all over the world [1]. The unstable oscillation between a generator and the rest system (lead to generator out-of-step) or between two interconnected sub-systems (lead to islanding) are the main form of the power system instability.

The final report of the North American blackout on august 14, 2003 points out that 290 units (about 52,745 MW) tripped during the cascading failures [2]. Among these tripping cases, a large portion occurred after the grid lost synchronism. The study shows that many generators shut the unit down early in the cascade for the pre-designed protection points, which exacerbated the problem. The generator protections should be set tight enough to protect the unit but also wide enough to assure it remains connected to the grid as long as possible. A reliable electric system requires proper protection and control coordination between power plants and the transmission system. Therefore, to evaluate the severity and the evolution trend of the oscillation is important for setting the protection relays. In [3], NERC (American Electric Reliability Corporation) suggests that the generator owner and transmission owner shall work together to complete the coordination process. The SPS (Special Protection Schemes) has been proposed for prevent the cascading failures of the power system, which take advantage of all the available protection and control devices to adjust the operation state of the power system to a more secure level.

When out-of-step occurs for one generator in the power system, the referring generator should be tripped off immediately to prevent the shaft from suffering mechanical vibration torque. Otherwise, the separation of the two interconnected sub-systems should be carried out as soon as possible when the out-of-step exists between the two sub-systems. The traditional protection schemes are based on mho/impedance relay analysis for the SMIB or two equivalent machine model, which may can't appropriately reflect the physical characteristics of the power system in real-time especially when the system suffers cascading failures. It is of great importance that the stability estimation act accurately since the generator trip or power grid islanding will worsen the instability of the whole system. The operators also prefer some alarm information before the generator tripping or system islanding so they can take some measures to prevent it from happening, such as load control or capacitor/reactor switching, et. al. Therefore, the analysis of the power system dynamics and the prediction of the out-of-step conditions as well as the discriminative criterion are all need to be studied.

2 Related works

The stability of the power system has been studied for several decades. Overall, these methods can be twofold: (1) Model-based method; (2) Signal-based method. The classical method normally analyse the power system based on a simplified model. It needs a trade-off between the accurate equivalence and the available mathematic tools. The signal based method further considers that the dynamic trajectory of the system can imply its physical feature in a certain extent. These two methods can be used for decreasing the possibility of the out-of-step conditions and detecting the out-of-step scenarios as soon as they occurred.

Currently, all the major generators with a capacity larger than 300MW need to set the out-of-step protection. And the interconnecting transmission lines need to install the out-of-step separation devices. Classical power swing detection methods based on concentric characteristic or blinders, which need a sophisticated study for the power system in order to determine the appropriate settings. But the settings are fixed and may lead to mal-operation as it can't adapt to the changing operation conditions of the system. In addition, the above mentioned methods are computationally complex and require a number of settings which must coordinate with each other. In general, it is too late for the operators' intervention to prevent the instability using the conventional out-of-step detection schemes. In recent years, the up-to-date intelligent algorithm, such as like SVM, FUZZY, Neural Network and energy like methods based on the synchronous measurement are being studied in a quantitative way [4, 5].

Reference [6] proposes a prediction method for power system out-of-step. The singular points of the power system are calculated before plotting the state plane trajectory. The eigenvalue analysis method is used for determining the stability margins of the system. The plane trajectory is derived from SIMB model and the time information is extracted from discretization with small intervals. In [7], the active power (P), reactive power (Q) and the slip of frequency (f) at two different times are measured and synthesized after clearing the faults (t1 and t2). Then the critical phase angle are determined and used to check whether the slip will be greater than zero using an equation set. In [8], the angle difference, slip frequency, and acceleration are then used to detect an out-of-step (OOS) condition in the electrical power system. It is an accurate discriminative criterion but can not predict the out-of-step conditions beforehand.

In [9], a predictive out-of-step tripping scheme is used for the national power system of by monitoring slip (rate of change of their relative phase) and acceleration (rate of change of slip). It is based on comprehensive transient stability studies using actual dynamical models. In [10], a predictive, transient stability monitoring scheme for generator out-of-step protection is presented based on a Lyapunov like method. The state of the simplified model is monitored and the predefined energy value is chosen as the discriminative criterion for the generator out-of-step. But it can't tell when it will lose synchronism. In [11], the coordination of power swing detection, distance protection and out of step protection is studied. The characteristics during the out-of-step are summarized and the basic principles for tripping the generator are discussed.

Some practical discriminative criterions have been proposed for estimating the out-of-step potentials of the static power system in an off-line manner. However, the pre-defined fault analysis, such as N-1 or N-2, can not meet the numerous or cascading disturbance circumstances in the power system. The parameter and disturbance independent online used methods are urgently needed to be studied both in the literature and industry.

With the more and more applications of PMUs and WAMS, the rotor angle of the generators and the phasor of the bus voltage both can be accurately measured with the asynchronous time step. So the angle stability can be more precisely analysed for the large area interconnected power systems.

There are different ways to measure the position of the spinning generator shaft so as to obtain the rotor angle directly. The most efficient way is as shown in Fig. 1. It only needs to apply equally-spaced and aligned reflective tape on existing generator shafts, then a laser emitter and optimal pickup are mounted on the generator and pointed at the shaft. The rising and falling edges are detected and transferred into PMUs in which the data process is done and the time-stamped rotor angle of the generator can be obtained with high accuracy. The retrofit is very simple and costless, which make it possible to obtain the synchronous rotor angle of all the generators in the power system with the help of WAMS.

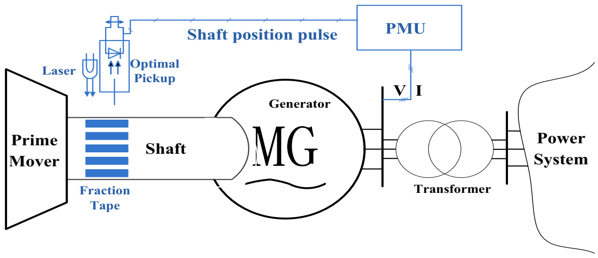

Figure 1. Rotor angle measurement

3 Basic theory and problem formulation

Mathematically, for a discrete signal F(k) ($k = 0, 1, 2, \dots N-1$, and N is the number of the sampling points), it can be expressed as a linear summation of M distinct modes :

$$y(k) = \sum_{i=1}^{M} B_i e^{\lambda_i k \Delta t} \tag{1}$$

via the following three procedures [12].

1) Solve a linear prediction model (LPM)

If the signal consist of damped sinusoids and the number of the sampling data is no less than twice of the mode number, i.e., $N \geq 2M$, then part of the sampled data can be represented as linear summation of the rest data. The above process can be illustrated as follows:

$$\begin{bmatrix} F_M \\ F_{M+1} \\ . \\ . \\ F_{N-1} \end{bmatrix} = -\begin{bmatrix} F_{M-1} & F_{M-2} \cdots & F_0 \\ F_M & F_{M-1} \cdots & F_1 \\ & . & \\ & . & \\ F_{N-2} & F_{M-2} \cdots & F_{N-M-1} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ . \\ . \\ P_M \end{bmatrix} \tag{2}$$

It can be rewritten in a compact form:

$$\mathbf{F} = \mathbf{\Phi}(F)\mathbf{P} \tag{3}$$

If N=2M, equation (3) is directly solvable; otherwise the least-square estimate of P can be obtained using the generalized inverse of matrix Φ as follows:

$$\mathbf{P} = (\mathbf{\Phi}^{\mathrm{T}}\mathbf{\Phi})^{-1}\mathbf{\Phi}^{\mathrm{T}}\mathbf{F} \quad (4)$$

2) Find the roots of the polynomial with coefficient of **P**
Solve for the roots (eigenvalues) of the following polynomial:

$$x^M + P_1 x^{M-1} + P_2 x^{M-2} + \ldots + P_{M-1}x + P_M = 0 \quad (5)$$

where the m*th* root is equal to e^{λ_m}.

3) Estimate the amplitude

Part of the linear equations representing F(k) with e^{λ_m} can be used for solving the amplitude B_M:

$$\begin{bmatrix} F_{k_1} \\ F_{k_2} \\ \vdots \\ F_{k_N} \end{bmatrix} = \begin{bmatrix} (e^{\lambda_1})^{k_1} & (e^{\lambda_2})^{k_1} \ldots (e^{\lambda_M})^{k_1} \\ (e^{\lambda_1})^{k_2} & (e^{\lambda_2})^{k_2} \ldots (e^{\lambda_M})^{k_2} \\ \vdots & \ddots \quad \vdots \\ (e^{\lambda_1})^{k_N} & (e^{\lambda_2})^{k_N} \ldots (e^{\lambda_M})^{k_N} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_M \end{bmatrix} \quad (6)$$

The compact form in matrix can be written as:

$$\mathbf{F} = \mathbf{\Lambda B} \quad (7)$$

If more than M samples are used, i.e. $N > M$, the least-square estimation of B can be solved by:

$$\mathbf{B} = (\mathbf{\Lambda}^{\mathrm{T}}\mathbf{\Lambda})^{-1}\mathbf{\Lambda}^{\mathrm{T}}\mathbf{F} \quad (8)$$

After the three procedures, the discrete signal F(k) can be approximately analysed using the analysis formula of (1). The fitness of formula (1) to the original signal data can be appraised by signal-to-noise-ratio (SNR) [13], which is defined as:

$$SNR = 20\log\left(\|y(k)\| \,/\, \|/y(k) - \hat{y}(k)\|\right) \quad (9)$$

where $\|y(k)\|$ and $\|y(k) - \|\hat{y}(k)\|\|$ are the second norm of the measured signal and the norm of the error signal between the measured and estimated signals, respectively. Normally, it required that $\mathrm{SNR} \geq 20$ for a good fitting.

The advantages lie in the above transformation is that the characteristic of the discrete signal F(k) and the corresponding physical system can be evaluated in a more analytical way. Referring to the out-of-step problem, which initially reflects with the exponential separation or divergent oscillation of the rotor angle between one generator and the rest power system or between two sub-systems, the Prony algorithm can be potentially used for analysing the rotor angle trajectory.

During the dynamic process of the interconnected power system after a disturbance, the generators can be divided into two groups according to their movement characteristics. The generators with similar acceleration rotation speed in a certain time can be seen as coherent group. Assume generators i to n are identified as one coherent group, then accordingly, the centre of inertia (COI) reference can be calculated as:

$$\begin{cases} M_{sum} = \sum_{i=1}^{n} M_i \\ \omega_{\mathrm{COI}} = \sum_{i=1}^{n} \frac{M_i \omega_i}{M_{sum}} \\ \delta_{\mathrm{COI}} = \sum_{i=1}^{n} \frac{M_i \delta_i}{M_{sum}} \end{cases} \quad (10)$$

where M_{sum}, ω_{COI} and δ_{COI} are the inertial, equivalent speed and equivalent rotor angle of the coherency clusters, respectively. The rotor angle between the generator and the COI of the rest generators or between the COIs of the two groups is the direct discrimination criterion for the out-of-step conditions. Generally speaking, if the rotor angle difference is greater than 180° implies that out-of-step condition occurs.

Furthermore, the trajectory of the rotor angle difference in the future can be used for predicting the out-of-step conditions. In the power system, as the inertia characteristics of the power system, the oscillation dynamics of the rotor angle will not change swiftly. The rotor angle signal sampled in the past can be potentially used for predicting the movement trend of the rotor angle using Prony algorithm after some improvement.

4 Improvement of the Prony algorithm

4.1 The parameterization for Prony algorithm

There are three parameters in Prony analysis: Sampling frequency, the number of the data points and the order of the system. The basic principles for defining the parameters in the application of out-of-step detection and prediction are illustrated in the sequel.

Low frequency oscillation (0.1Hz~2.5Hz) is the potential danger for out-of-step of the power system. For interconnected power systems, the extra-low frequency oscillation needs to be concerned more particularly. Therefore, a sampling frequency of 25Hz is enough for out-of-step monitoring.

The number of the data points should cover at least one cycle of the oscillation with the possible lowest frequency. In practical use, several cycles of oscillation should be covered in order to derive the changing trend information. However, the rapid attenuation of the signal will be omitted if the time window is too long. Trade off must be made between the accuracy and the rapidity when choosing the length of the time window. Generally, 8s can be chosen as the time window for Prony analysis and there are total 200 data points during the data process.

The pre-assumed order of the system model is critical to the performance and accuracy of the Prony analysis. In the past, trier and error method is used for choosing the best order from 1 to half of the dada point number. The one with the least *SNR* is seen as the proper order. However, the prediction of the trajectory is not only relative to the accuracy of the curve fitting for the current signal wave but also to the stability or smoothness of the trajectory in the future. Define the diverging index of the Prony process as:

$$\mathrm{DI_m} = |\, e^{\lambda_m} | \quad (11)$$

which represents the divergence characteristic of the Prony curve fitting and the prediction. A supplementary stability index is defined as:

$$SSNR = SNR / \max(\mathrm{DI}_m) \quad (12)$$

It is used for evaluating the numerical stability of the prediction performance of the Prony algorithm, along with the SNR. So the order of the model can be chosen as the one with the optimal SSNR as shown in Fig. 2.

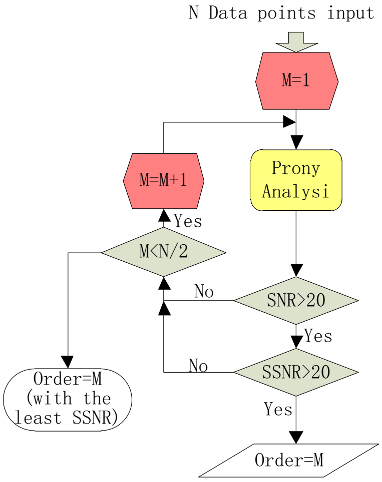

Figure 2. The order determination procedure

4.2 Energy index based order reduction

The order obtained via the above process could be a very large number. The order number of the Prony algorithm in the oscillation trajectory analysis is corresponding to the oscillation mode. But actually not each mode is equally important for the analysis of the physical nature. The out-of-step will happen when the oscillation energy keeps increasing. According to the physical meaning of the oscillation, define generalized oscillation energy as:

$$Energy_j = \sum_{i=1}^{N} |y(i)|^2 \quad (13)$$

The dominant oscillation modes will contribute a big proportion of the oscillation energy of the interconnected power system. The omission of the trivial energy components of the non-dominant oscillation modes will not significantly affect the dynamic movement characteristics of the power system. But it will reduce numerical instability in the prediction as the exponential expansion of the diverging index could exist in the omitted modes.

Suppose the generalized energy of the kth oscillation mode is:

$$Energy(k) = |B_k|^2 \cdot \sum_{i=1}^{N} \left| e^{\lambda_k i \Delta t} \right|^2, \; k = 1,2,...,M \quad (14)$$

Then sort the energy array in descending order, and denote K' is the data array after sorting. Generally, the sum of the energy of the first a few number (H) of oscillation modes will contribute a big proportion of the total energy of the signal, denote it as:

$$E_H = \sum_{j=1}^{H} Energy[K'(\mathrm{j})], \; j = 1,2,...H \quad (15)$$

If the following inequality holds:

$$E_H / Energy \geq 99\% \quad (16)$$

Then the curve fitting and prediction of the input data can be represented in a smaller number of the oscillation modes, as:

$$\tilde{y}(k) = \sum_{i=1}^{H} B_{K'(i)} e^{\lambda_{K'(i)} k \Delta t}, \; k = 1,2,...N, N+1,..., N+P \quad (17)$$

In this case, the order of the input signal is reduced and the numerical instability potential will be significantly decreased. The first N points data of $\tilde{y}(k)$ can be seen as the curve fitting to the original data points. The rest P points of data are the prediction of the trajectory signal which can be used for predicting the out-of-step condition.

5 Simulation results

The two-area power system shown in Fig. 3 is chosen as the example to verify the prediction scheme proposed in this paper. The parameters of the system can be found in [14]. Assume that a permanent three phase circuit short fault happens on bus 8 at 1.8s, after 100ms, part of the sectionalized bus is disconnected from the power grid by tripping one of the parallel transmission line between bus 7 and 9. Then the power system undergoes a dynamic oscillating process and after about 20.8s the system losses synchronization.

The PMUs are installed for every generator and the synchronous shaft position data will be sent to the control centre. The coherent grouping is carried out and the rotor angle between the two groups is calculated. The rotor angle between the two equivalent sub-systems is recorded and predicted via the improved Prony algorithm, the out-of-step conditions is monitored and predicted. As shown in Fig. 4, the rotor angle difference between every two generators is obtained via simulation. It can be seen that after 20.5s the angle difference is larger than 180°, which means the out-of-step occurs.

The rotor angle between the COI centres of sending sub-system (comprising of G1 and G2) and receiving sub-system (comprising of G3 and G4) is calculated, monitored and predicted using the proposed improved Prony algorithm. The Prony analysis is conducted once in every 0.5s, as it is computationally cost and not necessary to be re-conducted for every new data point. Fig. 5 shows the measured and the predicted value of the rotor angle between the COI of the sending and receiving groups. We can see that the predicted rotor angle trajectory is similar to the recorded one, which means that improved Prony algorithm is feasible in predicting the movement trend of the rotor angle different after decomposing the oscillation curve using the improved Prony algorithm.

The out-of-step detection is more straightforward as the rotor angle difference is directly used for judging the loss of synchronization. The alarm signal, which is multiplied by 180 in order to give a direct impression, is also shown in Fig. 5 with dashed line. It can be seen that the out-of-step condition is predicted about 5s before it truly happens, which gives the operators with opportunities to prevent the out-of-step and the islanding of the power system using some corrective measures, such as reducing power generation, controlling the power flow and supplementary damping control (HVDC or FACTS if possible).

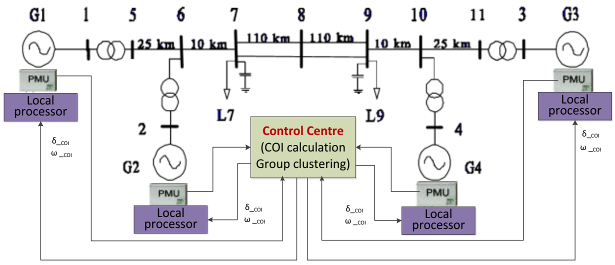

Figure 3. Two-area four-machine power system

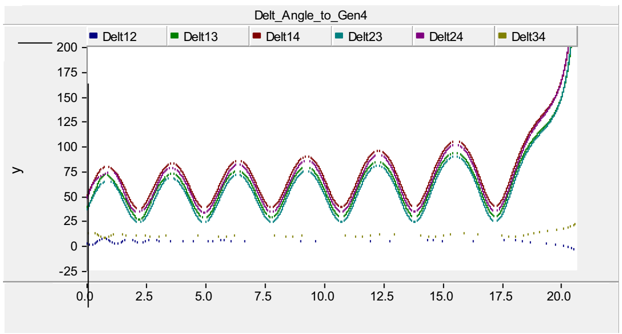

Figure 4. Rotor angle between the generators

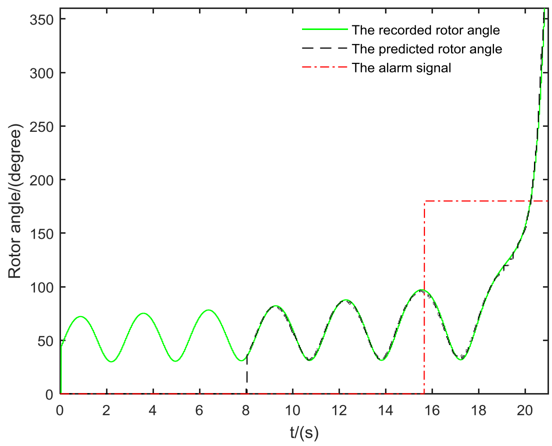

Figure 5. Predicted rotor angle via improved Prony algorithm.

6 Conclusion

With the increasing application of the PMU and WAMS in power system, an improved Prony algorithm is proposed for the out-of-step detection and prediction of interconnected power grids. The energy approximation method is used to reduce the order of the decomposed signals in order to improve the numerical stability of the prediction. The effectiveness and accuracy of the scheme is verified on a 2-area 4-machine power system.

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