MODERN PROTECTION PHILOSOPHY FOR SMART GRIDS

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ABSTRACT

This paper presents a modern power system protection philosophy for Out-Of-Step (OOS) detection that can be used in a proposed smart protection relays in smart grid applications. The protection philosophy depends on a combinational/hybrid algorithm between online energy function and online rotor angle/angular speed characteristics. The hybrid algorithm increases power system security due to accurate OOS detection. The hybrid algorithm overcomes the demerits of conventional OOS detection algorithms employed in conventional relays in current grids or smart grids. The hybrid algorithm is tested using Single Machine Infinite Bus (SMIB) to ensure the validity, effectiveness, reliability, and security upon the operation of the power system grids or/and smart grids.

KEYWORDS

Smart grids, out-of-stability, protection relays, critical clearing time, energy function, online stability, distance protection, power swing.

I. INTRODUCTION

The European Technology Platform Smart Grid (ETPSG) defines the smart grid as follows: A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.

Based on ETPSG definition, Smart Grid employs innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies to:

- Better facilitate and manage the connection and operation of all sources of energy.
- Give consumers more choice so they can help to optimize energy use.
- Provide consumers with greater information and choice of supply.
- Significantly reduce the environmental impact of the whole electricity supply system.
- Deliver enhanced levels of reliability and security of supply.

Smart Grid deployment creates "observability" across the entire energy chain: It deploys information and communications technologies to link devices and information, market and commercial considerations to engage users, environmental impacts, regulatory framework, standards for interoperability, managing social and government requirements, and transformation strategies to handle the new environment.

Modern power systems networks require a continuous monitoring, control, remedial actions in real-time events. OOS for interconnected power systems networks is a great computation challenge due to non-linear differential equations used in system simulation [1, 4-7]. So that, conventional protection relays detect the OOS using blinder characteristics with two steps or three steps either QUAD or MHO shape [2, 3]. Some manufacturers using the rate of change of impedance with respect to time that intersects the blinders for detecting the OOS like Siemens Company. Whereas, other manufacturers employed some timers that guarantee that the impedance stayed inside the blinders for certain time which means OOS and instant tripping should be happened like General Electric Company. The blinder characteristics method requires complex setting for drawing the adequate regions for power swing that blocks the distance function from abnormal tripping, and OOS that trips the associated circuit breakers [2, 3]. Thus, any setting error from user side could cause mal operation for the protection relay. Also, the blinders setting for generator protection and Over Head Transmission Lines (OHTLs) must be coordinated to trip the associated circuit breakers by selectivity. According to the above reasons an adaptive hybrid online monitoring and tripping algorithm is presented in this paper that can be implemented in smart protection relays equipped with Phasor measurement Units (PMUs).
The hybrid algorithm increases power system security due to accurate OOS detection. The hybrid algorithm overcomes

the demerits of conventional OOS detection algorithms employed in conventional relays in current grids or smart grids. The algorithm is adaptive and online since it is based on the online measurements via SPMUs for detecting system OOS. No settings are adjusted by the user and in turn no errors from user side that could make mal operation as in the case of the blinder characteristics method.

II. Conventional Transient Energy Function (TEF)

The transient stability detection involves the determination of whether or not synchronism is maintained after the machine has been subjected to severe disturbance. The equilibrium point of a dynamic system is stable if there a continuously differentiable positive definite function. If the total derivative is negative definite, then the equilibrium point is said to be asymptotically stable [7].

III. The Proposed Extended Energy Function

The Extended Energy Function (EEF) algorithm proposed in the paper is based on the classical power system model where generators are represented by constant voltage behind transient reactance. Consider single machine infinite bus system as shown in figure.1.

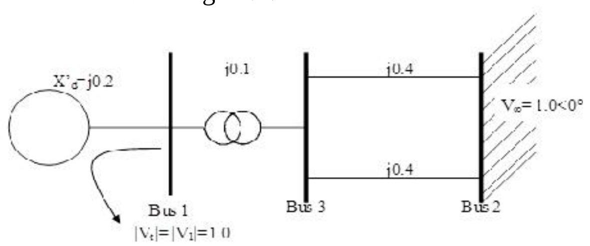

Figure.1: Single machine connected to infinite bus through two parallel lines

The swing equation of the above system can be expressed by the well-known differential equations:

$$\frac{d\delta}{dt} = \omega \qquad (1)$$

$$\frac{d\omega}{dt} = \frac{1}{M}(P_m - P_e - Dw) \qquad (2)$$

Where M is the generation inertia, P_m is the input mechanical power (P.u), P_e is the output electrical power (P.u), ω is the speed change of the generator rotor and δ is the rotor angle (deg.). The output electrical power of a power system is given by:

$$P_e = P_{\max} \sin\delta \qquad (3)$$

From equations (1), (2) and (3), the Post-fault equation of system given by:

$$M\frac{d\omega}{dt} = P_m - P_{e-postfault} = P_m - P_{\max-postfault}\sin\delta \qquad (4)$$

Integrating both sides give the system energy:

$$V(\delta,\omega) = \left[\int_0^{\omega} M\omega\, d\omega\right] + \left[\int_{\delta_s}^{\delta}\left[-P_m + P_{\max-postfault}\sin\delta\right]d\delta\right] \qquad (5)$$

Where subscript s denotes another stable equilibrium point in the post fault period

From equation (5), the energy function (V) of a power system is given by:

$$V(\delta,\omega) = \frac{1}{2}M\omega^2 - P_m(\delta - \delta_s) - P_{\max-postfault}(\cos\delta - \cos\delta_s) \qquad (6)$$

The time derivative of the energy function V in conjunction with equation (1) and (2) could be written as follow:

$$\frac{dV(\delta,\omega)}{dt} = -D\omega^2 \qquad (7)$$

By integrating equation (7) in the limit of [0, t] and equating it with equation (6), we can derive the following energy function V reflecting the damping effect:

$$V(\delta,\omega) = \frac{1}{2}M\omega^2 - P_m(\delta - \delta_s) - P_{\max-postfault}(\cos\delta - \cos\delta_s) + \int_0^t D\omega^2 dt \qquad (8)$$

In order to estimate the critical clearing time, critical clearing angle and the rotor speed, the differential equations of the fault system with damping are numerically integrated until the instant in which the state trajectory in ω-δ plot leaves the stable region of energy function which doesn't consider damping effect. This implies that the stable region should be extended. Also, this time will be an estimate of the critical clearing time and the total energy of the system is equal to the critical energy. State trajectories for different values of damping are plotted to obtain the relationship between the stable region and the damping constant. It has been shown through the tests that as the damping constant increases, the estimate of stability region also becomes larger.

To reflect the damping effect, it is necessary to change the associated damping term in Eq. (8) into an appropriate form. This can be done by using the contribution of the curve fitting method for the relationship between the stable region and the damping constant. The damping term can be written as:

$$\int_0^t D\mu^2 dt = K\mu^2 = (A_1 D^4 + A_2 D^3 + A_3 D^2 + A_4 D + A_5)\mu^2 \qquad (9)$$

Where A_1, A_2, A_3, A_4 and A_5 constants determined by the curve fitting method. As a result, we can easily obtain a new damping-reflected energy function for SMIB system as follows:

$$V(¢,\mu) = \frac{1}{2}M\mu^2 - P_m(¢ - ¢_s) - P_{max-postfault}(\cos¢ - \cos¢_s) + K\mu^2 \qquad (10)$$

The critical energy is evaluated where $¢ = ¢_u, \mu = 0$ as indicated in equation (11).

$$V_{cr} = -P_m(¢_u - ¢_s) - P_{max-postfault}(\cos¢_u - \cos¢_s) \qquad (11)$$

Where, subscript "u" denotes unstable equilibrium point in the post fault period. With the proposed energy function, transient stability detection is assured if the transient energy at the instant of fault clearing is less than the critical energy.

IV. Real-Time Transient Stability Algorithm

The algorithm is a combinational nature which consists of several stages. The first stage is the measurement via SPMUs, the second stage is the real-time EEF, while the third stage is the output tripping decision for the relevant circuit breaker.

The first stage employs the SPMUs to gather the required real-time phasors of voltages and currents to be used for direct calculations for obtaining the correlated values of rotor angle and angular speed.

Then the above calculated values will be conveyed to the pre-constructed EEF and plot the maximum energy contour, state trajectory. The smart protection relay (micro-controller based) is used to compare the results. If the state trajectory approaches or into borders the maximum energy contour, the algorithm provides an output operand states a system disturbance but the system will stay synchronized (Alarm message states normal power swing condition). If the state trajectory outside the maximum energy contours, the algorithm will stop and sends an output operand stating OOS (warning message, the system is OOS). Selectivity algorithm should be adopted to clear the faulted area only by selecting the appropriate circuit breaker to be tripped.

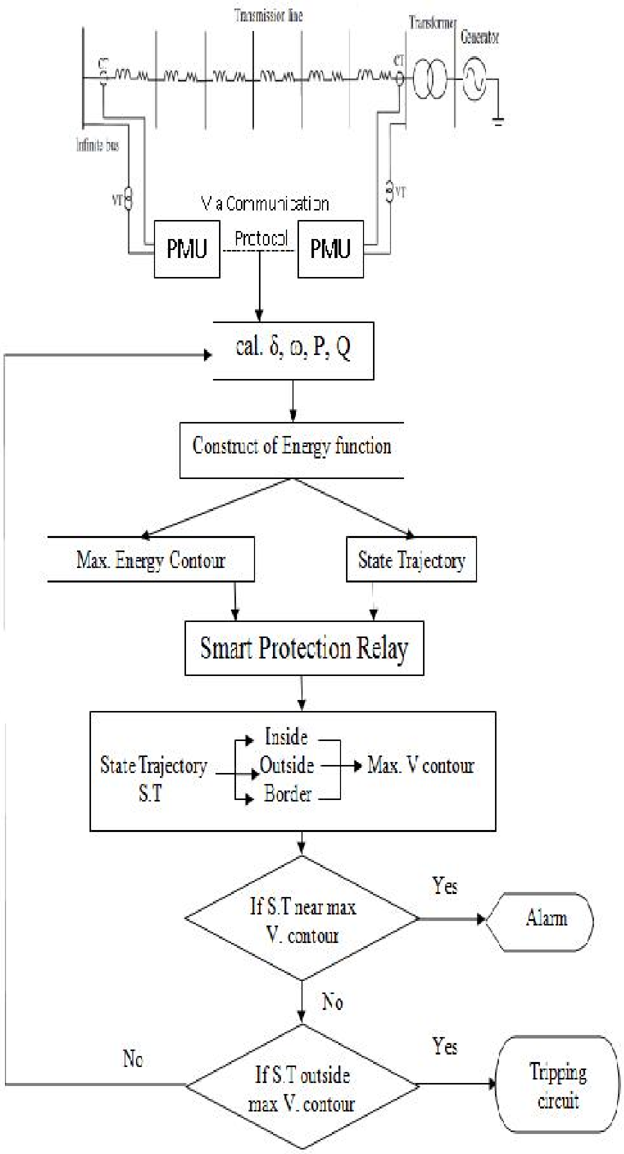

Figure.2: Smart Protection Algorithm

IV. Online Rotor Angle/Angular Speed OOS Detection ALGORITHM

This algorithm depends on the online values of the generator rotor angle and angular speed that can be calculated directly from the online currents and voltages via the Synchro-Phasor Measurement Units (SPMUs) [9, 11]. According to the above parameters the operating point locus can be detected and compared the maximum contour depicts the stability boundary (shown in red at figure.3). The algorithm detects the operating point if it is inside the stability contour; the algorithm initiates an output operand "NORMAL POWER SWING". Otherwise the algorithm initiates an output operand "OOS DETECTION".

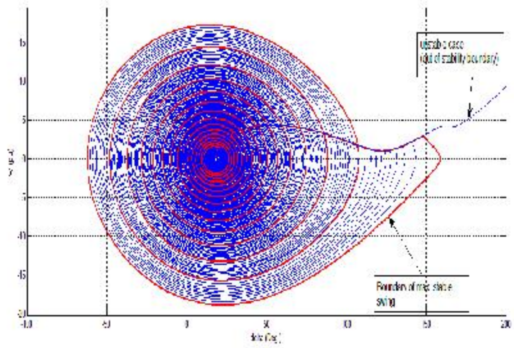

Figure.3: Operating point locus for several fault periods

V. The Proposed Hybrid Algorithm for OOS

According to the above analysis, EEF and online rotor angle/angular speed OOS detection algorithms are adequate for online assessment of OOS. In case of employing both of them into the same smart protection relays, more security and reliability are obtained according to the shown diagram in figure 4.

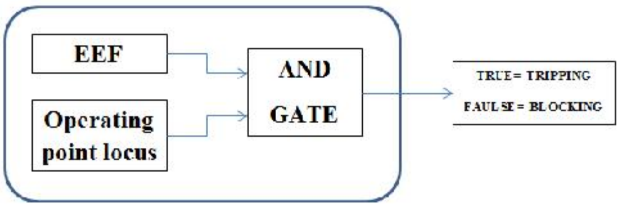

Figure.4: Modern hybrid algorithm for OOS.

VI. Simulation Results

The power test system used in this paper is the Single Machine Infinite Bus (SMIB) with two parallel lines as shown in figure.5. A three phase short circuit is simulated to occur at the beginning of one of the two Over Head Transmission Lines (OHTLs). Off-line simulation is made for obtaining the frequency response to be used as SPMU online measurements as per the algorithm to be used by the Modern hybrid algorithm for Modern Protection Relays (MPR) as shown in figure.6.

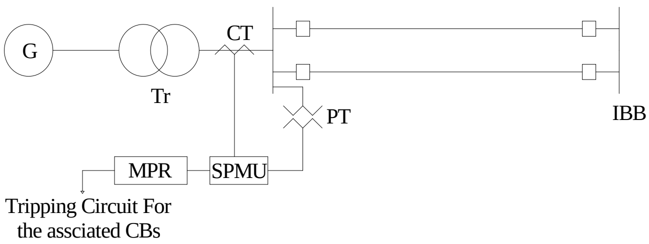

Figure.5: SMIB test system

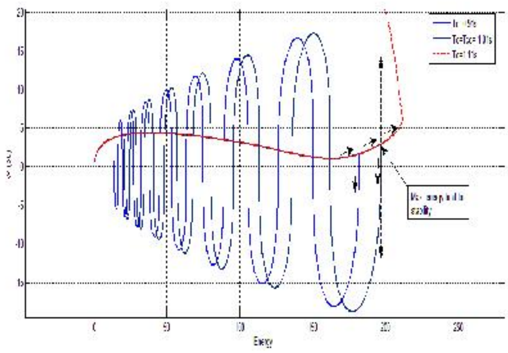

Figure.6: Angular speed response w.r.t energy

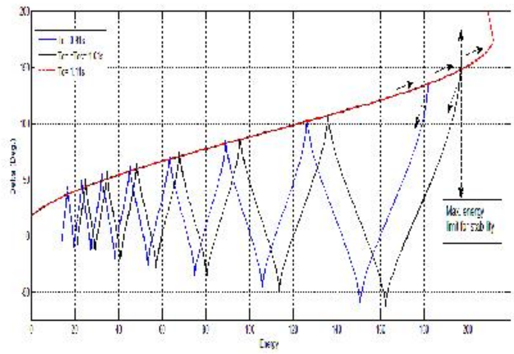

Figure.7: Rotor angle response w.r.t energy

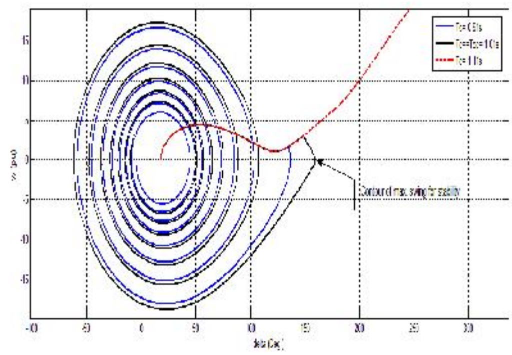

Figure.8: Operating point locus for three critical fault periods

Figures 6, 7, and 8 depict the nature of the required responses for OOS detection for Angular speed and rotor angle responses w.r.t energy as shown in figure.6 and figure.7. Whereas, figure.8 shows the operating point locus with respect to the maximum contour for stability.

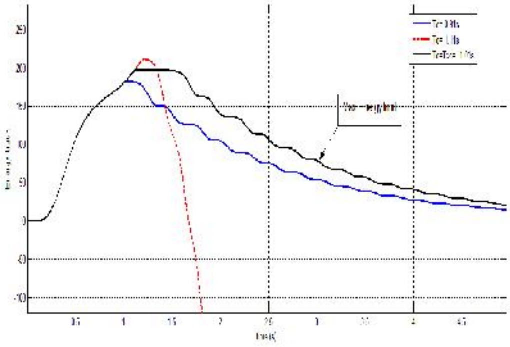

Figure.9: Energy value for three critical fault periods

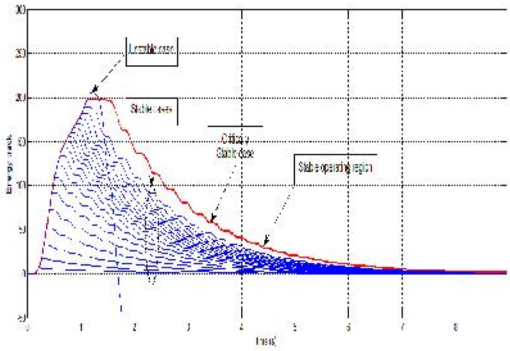

Figure.10: Energy value for several fault periods

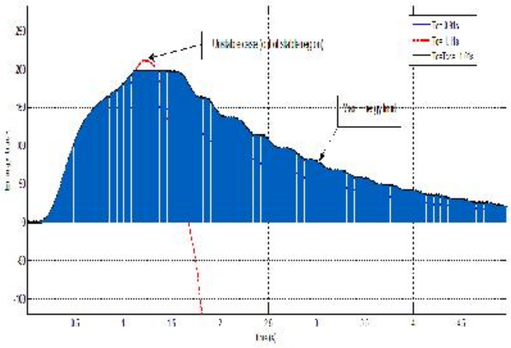

Figure.11: Stable operating region based on EEF

Figures 9, and 10 show the nature of the system energy with respect to time for critical and several fault period respectively. Whereas, figure 11 show the total stability region that is used by the algorithm for online stability detection.

Figure 12, show the time response of rotor angle for three critical fault periods.

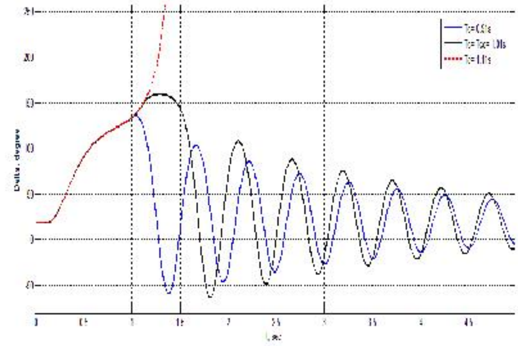

Figure.12: time response for three critical fault periods

Table 1: Validating the modern OOS algorithm

Case No.	*Fault Time (ms)*	*CTDM*	*Modern Algorithm*	*Remarks on the algorithm*
1	100	Stable	Stable	Distance Block
2	200	Stable	Stable	Distance Block
3	300	Stable	Stable	Distance Block
4	400	Stable	Stable	Distance Block
5	500	Stable	Stable	Distance Block
6	600	Stable	Stable	Distance Block
7	700	Stable	Stable	Distance Block
8	750	Unstable	Unstable	Trip
9	800	Unstable	Unstable	Trip
10	900	Unstable	Unstable	Trip

VII. CONCLUSIONS

The paper presented a modern power system protection philosophy for Out-Of-Step (OOS) detection that can be used in a proposed smart protection relays in smart grid applications. The protection philosophy depends on a combinational/hybrid algorithm between online energy function and online rotor angle/angular speed characteristics. The hybrid algorithm increases power system security due to accurate OOS detection. The hybrid algorithm overcomes the demerits of conventional OOS detection algorithms employed in conventional relays in current grids or smart grids. Regarding the detection of the maximum stability contour, an artificial intelligent technique could be used to be detected via generator parameters and online SPMUs for more accurate and adaptive algorithm.

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