Out-of-Step Protection for Multi-Machine Power Systems Using Local Measurements

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Abstract—The classical equal area criterion in the power-angle domain, which is typically used for power systems planning/stability studies, is modified to the time domain for out-of-step protection. Wide-area measurements are necessary to obtain the power-angle information if the traditional equal area criterion is applied for out-of-step detection. However, its time-domain modification requires only the information local to the out-of-step relay. The proposed method evaluates the transient energy, which is the area under the power-time curve, and by comparing the areas, differentiation between stable and out-of-step swings is made. The proposed method can be directly applied to multimachine power systems without network reduction, unlike the conventional equal area criterion in which the equivalent two area of the multimachine system needs to be obtained. The proposed out-of-step detection method has been tested on a Single Machine Infinite Bus System and a 17-Bus Multimachine system.

Index Terms—Power system relaying, Power system stability, Equal area criterion, Out-of-step, Multimachine power system.

I. INTRODUCTION

Disturbances in power system can lead to an unstable operating condition called out-of-step or loss-of-synchronism. Out-of-step relays are equipped to detect such conditions in the power system and disconnect a part of the system at pre-selected locations to bring the rest of the system back to a new stable operating condition [1], [2].

Conventional out-of-step detection techniques use a distance relay with blinders in the impedance plane and a timer. Setting blinders and timer settings require information on the fastest power swing, normal operating region, possible swing frequencies, etc. [1], [3]. Offline stability studies are needed to obtain the settings of the blinders and timer[4], [5].

Monitoring the rate of change of swing center voltage (SCV) and comparing it with a threshold could be used to differentiate stable and out-of-step swings. With some approximations, the SCV is obtained locally from the voltage at generator's terminal. However, the approximation is true only if the total system impedance is close to 90° [6]. In multimachine configurations, location of SCV (which is a virtual center), is not fixed, and thus the measurements at out-of-step relay location do not provide accurate approximation of the SCV.

Reference [7] proposes out-of-step detection based on neural networks and [8] proposes the application of fuzzy logic using adaptive network based fuzzy interface (ANFIS) for out-of-step detection. The training process could be time consuming and also the complexity increases as the system interconnections increase.

Reference [9] proposes the energy function criterion for loss-of-synchronism detection for a complex power system. During unstable swings, the entire power system oscillates in two groups and series elements (called cutset) connect them. To implement this technique as an out-of-step algorithm, measurements across all series elements are required to find the cutset. Therefore, this technique requires information from wide area measurement systems (WAMS) for out-of-step protection. However, the power systems need to be protected even in the absence or failure of WAMS, thus designing a protection algorithm that solely depends on local measurements is always valuable.

Reference [10] proposes an out-of-step detection technique based on equal area criterion (EAC) in power angle (δ) domain. The EAC technique is applicable only to two area power system. In order to implement it to a multimachine power system, an equivalent two area system has to be obtained first using one of the network reduction techniques (such as Centre of Inertia (COI) or Centre of Angle (COA) technique) [11], [12].

This paper used the concept of classical EAC, but modified to the time domain. The time domain EAC is based on the power-time (P_e-t) curve instead of the P_e-δ curve. An out-of-step protection methodology is proposed using the power-time (P_e-t) curve. The proposed EAC in time domain unlike the traditional EAC can be directly applied to a multimachine system without finding an equivalent two area system. For a multimachine system configuration, the generator's output power (P_e) from local voltage and current information is computed at the relay location. The transient energy of the generator, which is the area under the P_e-t curve, is then computed, and the swing is classified as stable or out-of-step based on the areas computed. The proposed algorithm has been tested on a Single Machine Infinite Bus and a 17-Bus Multimachine System using the software simulation tool (PSCAD™)[1] and the results have been presented. The proposed out-of-step detection has a significant potential in preventing system blackout even in absence or failure of WAMS.

The paper is organized as follows: Section 2 explains the

[1] PSCAD™ is the registered trade mark of Manitoba HVDC Centre, Winnipeg, Canada

basics of conventional EAC, the proposed technique (modified EAC in the time domain) and illustrations showing its application on a Single Machine Infinite Bus (SMIB) system. Section 3 explains the simulation results on a Single Machine Infinite Bus system, comparisons with an existing Blinder Technique, and simulation results on a 17-Bus Multimachine system. Conclusions drawn from the simulation studies are reported in Section 4.

II. Proposed Technique

Fig. 1 shows a SMIB configuration which is used to illustrate the proposed EAC in time domain.

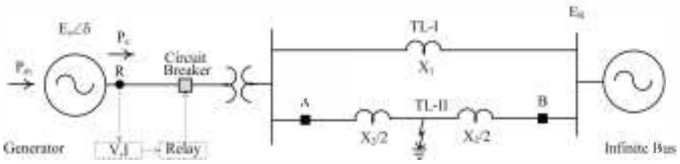

Fig. 1. A Single Machine Infinite Bus system.

In Fig. 1, the sending end voltage (E_s) leads the receiving end voltage (E_R) by δ. The angle δ is referred to as the relative rotor angle or power angle. The steady state output power of the generator is P_e and is equal to the input mechanical power (P_m) to the generator. The system has two parallel lines TL-I, TL-II with impedances equal to X_1 and X_2, respectively. The SMIB parameters are given in Appendix A.

A three phase fault is applied at the middle of TL-II. The fault is cleared with some delay by simultaneously opening the two breakers 'A' and 'B'. The transient response following a disturbance in the SMIB configuration is obtained if the swing equation (1) is solved using numerical integration techniques [13].

$$\frac{M}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e(\delta) \tag{1}$$

where, M is the generator inertia constant and ω_s is the system frequency [13].

The advantage of EAC in δ domain is that it describes the stability of the system without solving the swing equation. The difficulties associated with classical EAC in δ domain to detect out-of-step condition were discussed in the previous section. The proposed algorithm is based on the P_e-t curve and this information can be obtained directly from the measurements at relay location. Thus the proposed algorithm does not require the solution of the swing equation to obtain P_e-t curve.

Fig. 2 shows the P_e-δ curve for a stable system and Fig. 3 shows the P_e-δ curve for an unstable system, which are used to describe the EAC in δ domain. The corresponding P_e-t curves are shown in Figs. 4 and 5 and these curves are used to describe the proposed algorithm.

In Fig. 2 and 3, δ_0 represents power angle before the fault, δ_c represents power angle at the instance of fault clearance and δ_m represents the maximum swing angle (for a stable case). The EAC in δ domain tells that for a system to be stable, area A_1 is equal to area A_2 and area A_2 occurs before $\pi-\delta_0$. For an unstable system, the area A_1 is greater than area A_2 and the area A_2 occurs at $\pi-\delta_0$. The maximum swing of δ i.e. δ_m for a stable swing is less than $\pi-\delta_0$ [13].

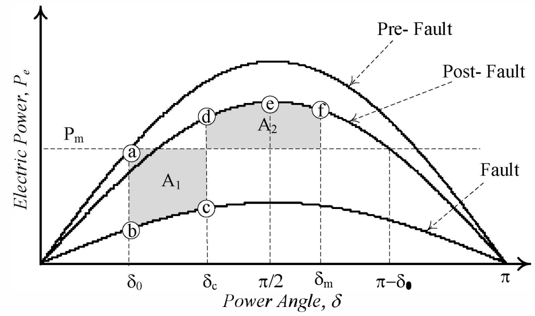

Fig. 2. P_e-δ curve for stable system.

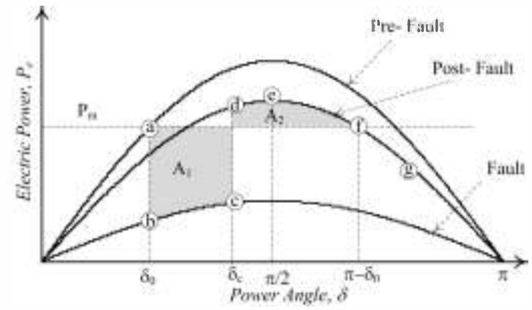

Fig. 3. P_e-δ curve for unstable system.

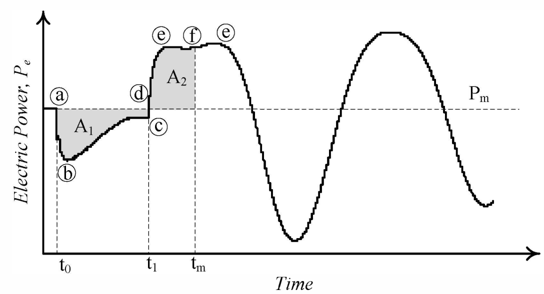

Fig. 4. P_e-t curve for stable system.

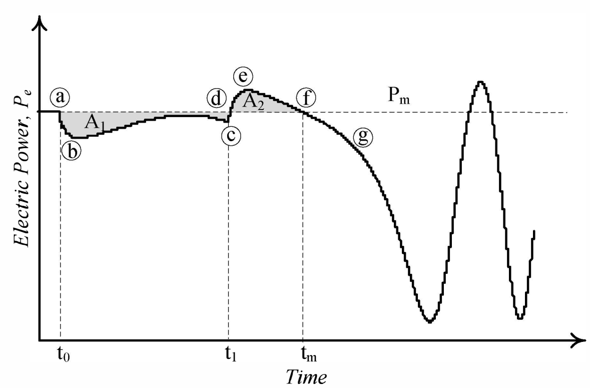

Fig. 5. P_e-t curve for unstable system.

The mathematical expressions to evaluate area A_1 and A_2 in time domain can be derived from the swing equation (1) [14]. Let the speed deviation of the rotor is ω_r, then,

$$\omega_r = \omega(t) - \omega_s = \frac{d\delta}{dt} \quad (2)$$

where ω(t) is the speed of the rotor during transient. From (1) and (2),

$$\frac{M}{\omega_s} d\omega_r = (P_m - P_e(\delta))dt \quad (3)$$

Integrating (3),

$$\frac{M}{\omega_S} \int d\omega_r = \int (P_m - P_e(\delta))dt \quad (4)$$

Area A_1 is obtained from (4) by setting the limit of integration from t_0 to t_1 (see Fig. 4 and 5). t_0 is fault inception time (corresponding power angle is δ_0) and t_1 is the time when P_e exceeds P_m line. Note that at t_0, the speed deviation is zero because the speed of the rotor is synchronous speed.

$$A_1 = \int_{t_0}^{t_1} (P_m - P_e(t))dt = \frac{M}{\omega_s}(\omega_r|_{t_1} - \omega_r|_0) \quad (5)$$

The area A_1 is positive as $P_m \geq P_e$ for $t=t_0$ to t_1. Similarly, area A_2 is obtained from (4) by setting the limit of integration from t_1 to t_m.

$$A_2 = \int_{t_1}^{t_m} (P_m - P(t)_e)dt = \frac{M}{\omega_s}(\omega_r|_{t_m} - \omega_r|_{t_1}) \quad (6)$$

Where t_m is the time when $\delta = \delta_m$. The area A_2 is negative as $P_m \leq P_e$ for $t=t_1$ to t_m. For a stable system, at t_m, the speed of the rotor is synchronous speed, so the speed deviation is zero. For out-of-step condition, the speed of the rotor at t_m is greater than the synchronous speed. Thus, the total area for stable and out-of-step condition from (5) and (6) are given as follows,
For stable condition,

$$A = A_1 + A_2 = \int_{t_0}^{t_m} (P_m - P_e(t))dt = 0 \quad (7)$$

For out-of-step condition,

$$A = A_1 + A_2 = \int_{t_0}^{t_m} (P_m - P_e(t))dt > 0 \quad (8)$$

Equations (7) and (8) are the expressions for EAC in time domain which tells that during the transient, if area A_1 and A_2 under the P_e-t curve are equal, the system becomes stable. But if area A_1 becomes greater than area A_2, the system goes to an out-of-step condition. The area under the P_e-t curve represents energy: a balance of transient energy ($A_1 + A_2 = 0$) results in a stable swing whereas, an imbalance in transient energy ($A_1 + A_2 > 0$) results in an out-of-step swing.

For implementation purpose, integrations in (7) and (8) are approximated by summation and P_m is set to P_e before the fault inception. The time limits are also expressed in terms of P_e. Thus for stable condition the total area A, which is equal to $A_1 + A_2$, becomes

$$A = \sum_{t_0}^{t_m} (P_m - P_e(t))\Delta t = 0 \quad (9)$$

For out-of-step condition,

$$A = \sum_{t_0}^{t_m} (P_m - P_e(t))\Delta t > 0 \quad (10)$$

where,

t_0 : Time when $P_e(t) < P_e|_{t-\Delta t}$ first occurs

t_m : Time when the total area $A|_t = 0$ (stable) or the time when $P_e(t)|_{t-\Delta t} > P_m$ and $P_e(t)|_t \leq P_m$ (out-of-step case)

In (9) and (10), Δt represents the sampling interval i.e. the time after which a new value of P_e is calculated. Equations (9), (10) along with the conditions for t_0 and t_m form the proposed algorithm for out-of-step detection. Based on the above equations, decision regarding stable or out-of-step condition is made at $t = t_m$ (time corresponding to $\delta=\delta_m$ or $\pi-\delta_0$ in the P_e-δ domain) with an error of Δt or less.

III. Case Studies

PSCAD™ models of a Single Machine Infinite Bus System and a 17-Bus Multimachine System were developed and the proposed methodology was tested [15].

A. Single Machine Infinite Bus System

A power system as shown in Fig. 1 is used first to test the proposed algorithm in a SMIB configuration [16]. The system parameters are given in Appendix A. Different power swings are obtained by applying a three-phase fault at the middle of a transmission line (TL-II) and clearing the fault by opening the breakers A and B simultaneously at two ends of the transmission line. Stable and out-of-step swings are obtained by operating the power system at different pre-fault conditions and varying the fault duration time.

In the case studies, generator's pre-fault power angle is set at 30°. Four case studies are simulated with fault duration time of 0.167, 0.20, 0.233, and 0.267 s. The first two cases result in stable swing, while the remaining two cases result in out-of-step condition.

With the fault duration of 0.167 s, the decision is made at 0.64 s as stable swing, when the calculated acceleration area become equal to deceleration area (0.048 p.u-s). By increasing the fault clearing time to 0.20 s, large oscillations in swing are observed. It takes 0.85 s to decide the swing as a stable swing. The time taken is larger than the previous case because the acceleration area is increased.

The fault duration time is further increased to 0.233 s. The acceleration area is 0.061 p.u-s, and the maximum available deceleration area is 0.027 p.u-s. The total area calculated is not zero, so this is an out-of-step condition and is decided at 0.598 s. Next, the fault duration time is set to 0.267 s, the acceleration area increases to 0.067 p.u.-s, and the out-of-step condition is detected at 0.504 s. Note that the decision made is faster compared to the previous case because the maximum deceleration area has reduced to 0.016 p.u.-s. The results of above four simulation cases are summarized in Table I.

TABLE I
SUMMARY OF SIMULATION RESULTS FOR SMIB SYSTEM

Case	1	2	3	4
Fault duration time, s	0.167	0.20	0.233	0.267
Area (A_1), pu-s	0.048	0.054	0.061	0.067
Area (A_2), pu-s	-0.048	-0.054	-0.027	-0.016
Area A_1+A_2, pu-s	0	0	0.033	0.051
Decision time, s	0.64	0.85	0.598	0.504
Decision	Stable	Stable	OS	OS

OS: Out-of-step

The performance of proposed out-of-step detection algorithm is also compared with existing Blinder technique (particularly the concentric rectangle scheme). An impendence relay with concentric rectangle schemes is located at one end of the TL-I (in the SMIB system shown in Fig. 1) which protects 80% of the line. Power swing in TL-I is achieved by applying fault at the middle of TL-II and opening breakers A and B simultaneously with different time delay. Detailed guidelines used for relay settings are described in Appendix B [17].

In the comparative case study, pre-fault power angle is set δ=30° and the fault clearing time is set to 0.233 s (Case 3 in Table I). To detect that the system is out-of-step, concentric rectangular scheme takes 4.93 s. The locus of swing is shown in Fig. 6. The swing alone takes 0.458 s to traverse the two concentric rectangles. For this case, the proposed algorithm takes just 0.598 s to detect that it is out-of-step.

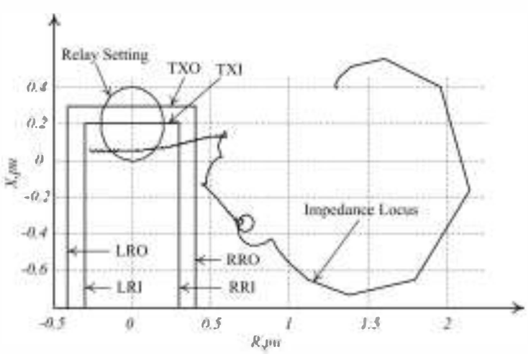

Fig. 6. Out-of-step locus for fault duration of 0.233 s and δ=30°.

The simulation results show that the proposed algorithm is accurate and much faster compared to the conventional concentric rectangular scheme. Note that the decision time for a concentric rectangular scheme depends on the guidelines used for the relay settings. Besides, finding the required settings for concentric rectangular method is not straightforward. It depends on the system parameters, whereas the proposed algorithm is independent of the system parameters, which is quite a useful advantage.

B. 17 Bus Multimachine System

A power system as shown in Fig. 7 is considered for testing the proposed algorithm on a multimachine system. The power system has 17 buses (B1-B17), 8 transformers (Tr1-Tr8) and 14 transmission lines (T1-T13). The system has two synchronous generators (Gen1 and Gen2), two motor loads (M1 and M2) and four static loads (L1-L4). The details of the power system parameters are given in Appendix C.

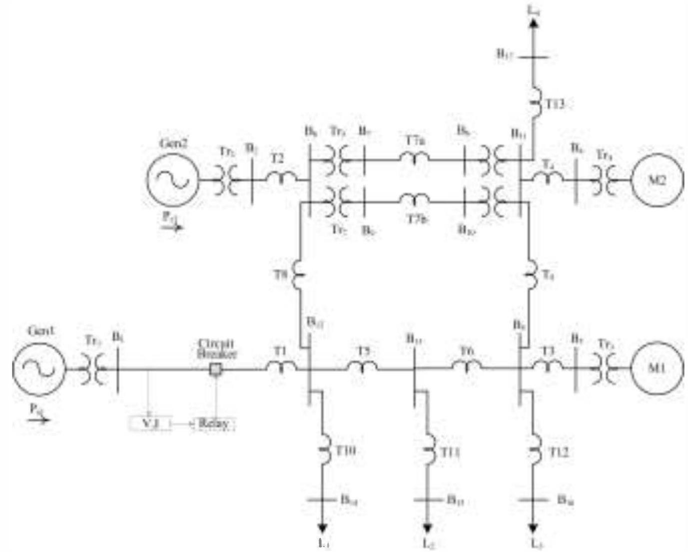

Fig. 7. A 17-bus multimachine power system.

Various simulations are carried out with three phase fault applied at the middle of the transmission lines T5, T7a, T9. Fault clearing times and the total system load are varied to obtain various natures of stable and out-of-step swings. The out-of-step relay is installed close to Gen1 as shown in Fig. 7, which protects the system when Gen1 goes out-of-step. The voltage and current information at the Gen1's terminal is used to compute the output power of Gen1.

Gen1 and Gen2's output powers are 0.8345 and 0.4091 p.u., respectively, and they are supplying a total system load of 1.2436 p.u. A three phase fault is applied at the middle of the transmission line (T9) and duration of fault is set at four different values 0.14, 0.147, 0.148 and 0.160 s, respectively. In the first case, the area A_1 is found to be 0.1009 p.u.-s and the area A_2 becomes -0.1009 p.u.-s at 1.0265 s. Since the total area becomes zero, this case is decided as a stable swing at 1.0265 s. The P_e-t curve for this case is shown in Fig. 8. The results are listed under Case 5 column in Table II.

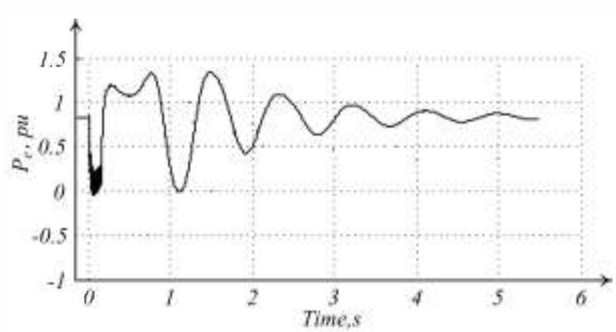

Fig. 8. P_e-t curve for fault applied at the middle of T9 and cleared at 0.14s.

Another case where fault duration time is increased to 0.147s is described next. The area A_1 increases to 0.1024 p.u.-s, the area A_2 becomes -0.1024 p.u.-s at 1.0881 s, and this case is decided as a stable swing at 1.0881 s. The results are listed in Table II - Case 6.

The fault duration time is next increased to 0.148 s from 0.147 s. The P_e-t curve is shown in Fig. 9. The area A_1 is found to be 0.1051 p.u.-s, while the area A_2 is found only to be -0.0753 p.u.-s at 1.0249 s. The total area A for this case is 0.0298 p.u.-s, which is greater than zero, so this case is decided as an out-of-step swing at 1.0249 s. The results are listed in Table II - Case 7.

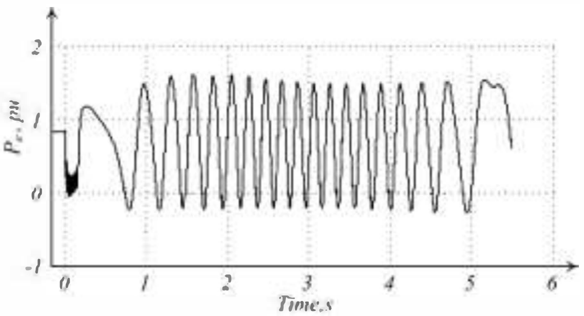

Fig. 9. P_e-t curve for fault applied at the middle of T9 and cleared at 0.148 s.

The fault duration is increased to 0.16 s. The area A_1 and A_2 are found to be 0.1103 p.u.-s and -0.0584 p.u.-s, respectively. This case is decided as out-of-step swing at 0.9329 s as the total area becomes 0.0555 p.u.-s. The results obtained are summarized in Table II – Case 8.

In the next set of simulations, the fault location is changed to the middle of transmission line T5 and four different simulations are carried out with fault duration times of 0.08, 0.1, 0.101 and 0.11 s, respectively. The total system load is set at 1.3199 p.u., out of which Gen1 is supplying 0.8091 p.u., whereas Gen2 is supplying 0.5108 p.u. The out-of-step relay is installed at Gen1's terminal as shown in Fig. 7, which protects the system when Gen1 goes out-of-step with respect to the rest of the system. The summary of simulation results are shown in Table III.

TABLE II
FAULT APPLIED AT THE MIDDLE OF THE TRANSMISSION LINE T9

Case	5	6	7	8
Pre-fault Load, p.u.	1.2436	1.2436	1.2436	1.2436
Fault duration time, s	0.1400	0.1470	0.1480	0.1600
Area (A_1), p.u.-s	0.1009	0.1024	0.1051	0.1103
Area (A_2), p.u.-s	-0.1009	-0.1024	-0.0753	-0.0548
Area A_1+A_2, p.u.-s	0	0	0.0298	0.0555
Decision time, s	1.0265	1.0881	1.0249	0.9329
Decision	Stable	Stable	OS	OS

OS: Out-of-step

TABLE III
FAULT APPLIED AT THE MIDDLE OF THE TRANSMISSION LINE T5

Case	9	10	11	12
Pre-fault Load, p.u.	1.3199	1.3199	1.3199	1.3199
Fault duration time, s	0.0800	0.1000	0.1010	0.1100
Area (A_1), p.u.-s	0.0616	0.0765	0.0794	0.0833
Area (A_2), p.u.-s	-0.0616	-0.0765	-0.0663	-0.0483
Area A_1+A_2, p.u.-s	0	0	0.0131	0.0350
Decision time, s	0.8963	1.0914	1.2458	1.0039
Decision	Stable	Stable	OS	OS

OS: Out-of-step

The out-of-step relay is tried next at Gen2's terminal so that it protects the system when Gen2 goes out of step. The voltage and current information at the Gen2's terminal are used to compute the output power of Gen2. Four simulations are reported here with three phase fault applied at the middle of the transmission line T5, T7a, and T9. The pre-fault load and fault duration times are varied to obtain the various swings. The results are given in Table IV.

TABLE IV
RESULTS WHEN OUT-OF-STEP RELAY IS INSTALLED AT GEN2

Case	13	14	15	16
Pre-fault Load, p.u.	0.7326	0.7326	1.2162	1.325
Fault Location	Mid. Of T5	Mid. of T7a	Mid. Of T5	Mid. of T9
Fault duration time, s	0.0016	0.0016	0.1160	0.0910
Area (A_1), p.u.-s	0.01048	0.00091	0.8291	0.6981
Area (A_2), p.u.-s	-0.01048	-0.00091	-0.0215	-0.0146
Area A_1+A_2, p.u.-s	0	0	0.8076	0.6835
Decision time, s	0.6912	0.7326	1.6901	1.5256
Decision	Stable	Stable	OS	OS

OS: Out-of-step

Keeping the pre-fault power constant, and by increasing the fault duration, marginally stable and out-of-step conditions were obtained (similar to the previously listed Cases 6,7,10 and 11). For example, in Cases 6 and 7, the pre-fault load was set at 1.2436 p.u. and the fault duration time was increased from 0.147 to 0.148 s. The system was stable for fault duration of 0.147 s and became out-of-step when the fault duration was increased to 0.148 s. Increasing the fault duration time by small amount of 0.001 s caused the system to go to an out-of-step condition from a stable condition. When the fault duration time was increased by less than 0.001 s, simulation results did not show significant differences in calculated area, thus the above cases were treated as marginal cases.

Addition of machines adds more complexity to the system as the machines introduce more nonlinear dynamics in the system. Thus by testing the proposed algorithm for a multimachine system consisting of two motors and two generators, it was shown that additional machines do not compromise on the effectiveness of the proposed algorithm. As stated earlier, P_e was calculated from the local voltage and current measurements at generator's terminal. The out-of-step relay was only provided with P_e information of corresponding generator for which the out-of-step relay is installed, and was not provided with any other network parameters or network structure information. This makes the algorithm independent of system parameters and hence applicable to any multimachine system without reducing it.

IV. CONCLUSION

A technique for out-of-step detection by modifying the classical equal area criterion condition to the time domain was proposed in this paper. The stable and unstable points on the P-δ curves were mapped to the P vs t domain. The proposed technique was tested on a Single Machine Infinite Bus system and a 17-Bus Multimachine System and the results showed that it was able to detect the out-of-step conditions correctly. The proposed technique had another main advantage that it could be applied directly to a multimachine power system without obtaining an equivalent two area system. The differentiation between stable and out-of-step swings was done purely on the local voltage and current information available at the relay location and it did not need any line parameter information, nor any off-line system studies, which makes the proposed algorithm effective even in absence of failure of WAMS.

V. ACKNOWLEDGMENT

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APPENDICES

A. *SMIB Parameters*

Base MVA=2,220 MVA, Base kV=24 kV
Generator VA rating=4*555 MVA
Generator Voltage=24 kV
Direct Axis Transient Reactance (X_d') =0.3 p.u.
Inertia Constant (H) =3.5 MW-s/MVA
Frequency=60Hz
Infinite Bus Voltage=0.9 p.u., Transformer=j0.15 p.u.
TL-I=j0.5 p.u., TL-II=j0.93 p.u.

B. *Binder Settings*

Right Resistance-Inner (RRI) =0.3 p.u.
Right Resistance-Outer (RRO) =0.4 p.u.
Left Resistance-Outer (LRI) =-0.3 p.u.
Left Resistance-Inner (LRO) =-0.4 p.u.
Top Reactance-Inner (TXI) =0.2 p.u.
Top Reactance-Outer (TXO) =0.3 p.u.
Bottom Rectangles (BX) =-1.94 p.u.

C. *17 Bus Mutlimachine Parameters*

TABLE A.1. GENERATOR PARAMETERS

Generator	Gen1	Gen2
Rated Power (MW)	1500	2000
Rated L-L Voltage (kV)	15	15
X_d (p.u.)	0.866	0.866
Angular Frequency (rad/sec)	376.992	376.992
Inertia Constant (sec)	1.7	1.7

TABLE A.2. TRANSFORMER PARAMETERS

Name	MVA Rating	Voltage Ratio (kV)	X_d (p.u.)
Tr1	1500	15/500	0.1
Tr2	3000	15/500	0.1
Tr3	800	15/500	0.1
Tr4	900	15/500	0.1
Tr5	1000	500/735	0.1
Tr6	1000	735/500	0.1
Tr7	1000	500/735	0.1
Tr8	1000	735/500	0.1

TABLE A.3. MOTOR PARAMETERS

Motor	M1	M2
Rated Power (MW)	600	500
Rated L-L Voltage (kV)	15	15
Angular Frequency (rad/sec)	376.992	376.992

TABLE A.4. TRANSMISSION LINE PARAMETERS

Transmission Line	Length (km)	Reactance (p.u.)
TL1	120	0.1343
TL2	50	0.07
TL3	45	0.05603
TL4	160	0.0716
TL5	100	0.1166
TL6	60	0.0706
TL7a	130	0.0709
TL7b	130	0.0709
TL8	50	0.05431
TL9	45	0.04888
TL10	50	0.04888
TL11	50	0.05974
TL12	45	0.03258
TL13	45	0.04888

REFERENCES

[1] W. A. Elmore, *Protective Relaying Theory and Applications*, 2nd ed. New York: Marcel Dekker, 2004.

[2] C. R. Mason, *The Art and Science of Protective Relaying.* New York: Wiley, 1956.

[3] J. Holbach, "New Out of Step Blocking Algorithm for Detecting Fast Power Swing Frequencies," in *Proc. Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources,* 2006, pp. 182-199.

[4] Y. Liu and Y. Liu, "Aspects on Power System Islanding for Preventing Widespread Blackout," in *Proc. IEEE International Conference on Networking, Sensing and Control,* 2006, pp. 1090-1095.

[5] A. Mechraoui and D.W. P. Thomas, "A new principle for high resistance earth fault detection during fast power swings for distance protection," *IEEE Transactions on Power Delivery,* vol. 12, no. 4, pp. 1452-1457, Oct. 1997.

[6] D. Tziouvaras and D. Hou, "Out-Of-Step Protection Fundamentals and Advancements", in *Proc. 30th Annual Western Protective Relay Conference,* 2003, pp.282-307.

[7] A. Y. Abdelaziz, M. R. Irving, M. M. Mansour, A. M. El-Arabaty, and A. I. Nosseir, "Adaptive protection strategies for detecting power system out-of-step conditions using neural networks," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 145, no. 4, pp. 387-394, Jul. 1998.

[8] W. Rebizant, "Fuzzy logic application to out-of-step protection of generators," in *Proc. IEEE Power Engineering Society Summer Meeting,* 2001, vol. 2, pp. 927-932.

[9] R. Padiyar and S. Krishna, "Online detection of loss of synchronism using energy function criterion," *IEEE Transactions on Power Delivery,* vol. 21, no. 1, pp. 46-55, Jan. 2006.

[10] A. G. Phadke, A. Edris, J. Benton, M. Gaudi, and G. Michel, "An adaptive out-of-step relay [for power system protection]," *IEEE Transactions on Power Delivery,* vol. 12, no. 1, pp. 61-71, Jan. 1997.

[11] M. A. Pai, *Energy Function Analysis for Power System Stability*. Boston: Kluwer Academic Publishers, 1989.

[12] M. A. Pai, *Power System Stability :Analysis by the Direct Method of Lyapunov.* Amsterdam: North-Holland Pub. Co., 1981.

[13] W. D. Stevenson, *Elements of Power System Analysis*, 4th ed. New York: McGraw-Hill, 1982.

[14] S. Cheng and M. S. Sachdev, "Out-of-step protection using the equal area criterion," in *Proc. Canadian Conference on Electrical and Computer Engineering,* 2005, pp. 1488-1491.

[15] "PSCAD User Manuals," Manitoba HVDC Research Centre, Winnipeg, Canada.

[16] P. Kundur, *Power System Stability and Control.* New York: McGraw-Hill, 1994.

[17] IEEE PSRC WG D6, "Power Swing and Out-of-Step Considerations on Transmission Line," Final draft, Jun. 2005.