Protection and Control of
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ORIGINAL RESEARCH

An adaptive supervised wide-area backup protection scheme for transmission lines protection

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Abstract

Maloperation of conventional relays is becoming prevalent due to ever increase in complexity of conventional power grids. They are dominant during power system contingencies like power swing, load encroachment, voltage instability, unbalanced loading, etc. In these situations, adaptive supervised wide-area backup protection (ASWABP) plays a major role in enhancing the power system reliability. A balance between security and dependability of protection is essential to maintain the reliability. This paper proposes multi-phasor measurement units (MPMU) based ASWABP scheme that can function effectively during faults besides power system contingencies. MPMU is an extended version of Phasor Measurement Unit (PMU). It is an intelligent electronic device which estimates the synchronized predominant harmonic phasors (100Hz and 150Hz) along with the fundamental phasors (50Hz) of three phase voltages and currents with high precision. The proposed ASWABP scheme can detect the fault, identify the parent bus, determine the faulty branch and classify the faults using MPMU measurements at System Protection Center (SPC). Based on these MPMU measurements (received at phasor data concentrator (PDC) at SPC) the appropriate relays will be supervised to enhance the overall reliability of the power grid. Numerous case studies are conducted on WSCC-9 bus and IEEE-14 bus systems to illustrate the security and dependability attributes of proposed ASWABP scheme in MATLAB/Simulink environment. Also, comparative studies are performed with the existing conventional distance protection (Mho relays) for corroborating the superiority of the proposed scheme regarding security and dependability. Comparative studies have shown that the proposed scheme can be used as adaptive supervised wide-area backup protection of conventional distance protection.

Keywords: Adaptive supervised wide-area backup protection (ASWABP), Multi-phasor measurement unit (MPMU), Security, Dependability

1 Introduction

The ever-increasing demand for electricity causes conventional power grids to operate at their maximum operating limit. When the system is under such stressed condition, the occurrence of a static phenomenon like load encroachment or dynamic phenomena like power swings may result in maloperation of distance relays [1–5]. This paves the way for fairly reduced security in power system protection. The abridged security increases the dependability of the protection system [6]. However, balanced measures of security and dependability in a protection system are required

for the reliable operation of the power system under any operating conditions [7]. Therefore, developing an adaptive coordinated control of the protection system is a growing need for maintaining security-dependability balance [8, 9]. Emerging synchrophasor measurements based supervised backup protection methodologies can effectively maintain this balance and hence enhances reliability of the power system [10, 11].

Inordinate research attention is being received towards synchrophasor measurements based backup protection methods for transmission lines. Major research works rely on phasor measurement unit (PMU) based wide area measurement system (WAMS) and wide area protection system (WAPS) [12–17]. WAMS and WAPS incorporated in backup protection systems were named

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as a wide-area backup protection (WABP) system [18–23]. P.K. Nayak et.al, in their research work [18] have developed a WABP system based on sequence components of the bus voltages. With this proposed system, the authors could identify the bus nearer to the fault and faulty line. Based on these data, the relays to be operated are recognized. Hinge et.al [19] have developed WABP, which works based on segregated phase comparison technique. However, the methodologies proposed in [18, 19] may require recalibration of existing relays in terms of pickup criterion sensitivity. Hall et.al [20] have proposed a wide-area distributed current differential scheme for WABP of the transmission line. However, the accuracy of the proposed scheme is affected by the power system unbalances. Though, the differential protection is simple in principle, but not so easy for implementation because it depends on data synchronization on both sides of the line to be protected. Li et.al in their research work [21] have evaluated the performance of WABP under various power system disturbances. The research works proposed in [20, 21] requires PMUs to be placed at all the buses. Sheng et.al in [22], have implemented numerical relays based on intelligent electronic devices in coordination with other relay agents for maintaining security-dependability balance. J. Ma et.al [23] have developed a fitting factor based WABP. A fault condition is identified based on the higher value of the ratio between protection fitness function and protection fitness expectation function. To avoid maloperation of the relays with multi-zone protection during power swing condition, swing blocking and operating components must be added in Intelligent Electronic Devices (IEDs) [22, 23].
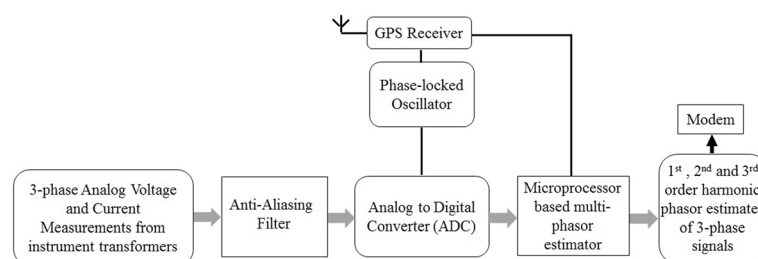
The proposed research methodology attempts to overcome the limitations and shortcomings of methodologies discussed above. The ASWABP scheme can effectively detect and classify the faults using harmonic phasor-estimates (50Hz, 100Hz and 150Hz) of three phase current signals obtained from MPMU for the backup protection of transmission lines. Equivalent harmonic coefficients (EHC), I_{EHC} of branches at all buses is calculated to identify the parent bus in the power system. Once the parent bus is identified, the deviation of EHC of all branches w.r.t parent bus is calculated to determine the faulty branch and corresponding relays to be supervised. Furthermore, the transient events other than faults such as power swings and load encroachment along with unbalanced load are detected by using the magnitude of the fundamental current phasor besides the second and third order harmonic current phasors magnitude. The performance of the proposed scheme is validated for different fault conditions (fault resistance (FR), fault inception angle (FIA) & fault distance (FD)) and other than fault events by carrying out extensive simulations on WSCC-9 bus and IEEE-14 bus systems.

2 Multi-phasor measurement unit

MPMU is an intelligent electronic device which can estimate the fundamental and predominant harmonic phasors (2nd and 3rd order) of three phase voltage and current signals. During a fault condition, waveform distortion, as well as the system unbalance occurs. These disturbances results the line voltages and currents to be non-sinusoidal in wave shape, consisting of second and third order harmonics as predominant [24–27]. Selection of 2nd and 3rd harmonic current phasors for fault analysis palys a major role in segregating the fault and non-faulted conditions. The major functional elements of MPMU are shown in Fig. 1, which is used for extracting the fundamental and harmonic current phasors. From Fig. 1 the analog three phase voltages and currents are converted into appropriate voltages by instrument transformers (CVT and CT) [6]. These signals are passed through the anti-aliasing filter to avoid the aliasing phenomenon. Analog to digital converter (ADC) converts these analog signals into digital signals. The phase-locked oscillator (PLO) ensures the time stamping of the voltage and current signals with the help of Global Positioning System (GPS) pulse per second. Microprocessor based multi-phasor estimator calculates the fundamental, second and third order harmonic phasors of three phase voltage and current signals using Discrete Fourier Transform (DFT).

Since fundamental, second and third order harmonic phasors of current signals are deployed in this paper for ASWABP, estimations of these current phasors are

Fig. 1 Block diagram of a multi-phasor measurement unit (MPMU)

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discussed below. DFT of discretized data obtained from ADC ($i(n\Delta T)$) is given by Eq. (1).

$$I(k) = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1}i(n\Delta T)e^{-j\frac{2\pi kn}{N}} \quad \text{for } k = 0, 1, ..N-1$$

(1)

where,

N = Number of samples per cycle,

n = sample number,

ΔT = sampling time = (1/sampling frequency)

= $(1/f_s) = (1/(N*f_0))$,

f_0 = fundamental frequency,

k = frequency order in terms of fundamental frequency,

DFT is calculated for every N number of samples ranging from n = 0 to N-1.

The harmonic current phasors are estimated by changing the value of k. For fundamental phasor extraction, the value of k is unity as given in Eq. (2). For second and third order harmonic phasor extraction, k holds the value of two and three- respectively as given in Eqs. (3) and (4).

$$I(1) = I_1 = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1}i(n\Delta T)e^{-j\frac{2\pi n}{N}}$$

(2)

$$I(2) = I_2 = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1}i(n\Delta T)e^{-j\frac{4\pi n}{N}}$$

(3)

$$I(3) = I_3 = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1}i(n\Delta T)e^{-j\frac{6\pi n}{N}}$$

(4)

The MPMU estimated current phasors at different buses in a Power system network are transmitted to PDC where SPC takes an appropriate action using ASWABP scheme. The following section discusses the development of proposed ASWABP scheme.

3 Methods

3.1 Adaptive supervised wide-area backup protection scheme

The backup protection plays a major role in increasing the dependability of the power system protection. This increased dependability is acceptable when the power system is in normal operating condition. However, when the system is being operated at its maximum operating limit, a false trip would result in greater damage. Hence, it is desirable to increase the security attribute of the protection system. The security-dependability balance is essential for reliable operation of a power system [6].

The dependability of the protection system is enhanced if all types of line faults are detected and classified accurately. Once the parent bus is detected then faulty branch will be identified and appropriate relays are supervised. The security is improved if all other events such as power swing, load encroachment and unbalanced loading are detected. The dependability and security attributes of the proposed methodology are elaborated through different case studies conducted on Western System of Co-ordinate Council-9 (WSCC-9) bus system in the subsequent sections. Third-order generator model with IEEE Type-1 exciter and distributed transmission line parameters as mentioned in reference [28] are used for modeling the WSCC-9 bus system shown in Fig. 2.

The positive and zero sequence parameters for 100 km length of the transmission line in WSCC-9 bus


Fig. 2 Single line diagram of Western State Coordinate Council −9 (WSCC-9) bus system
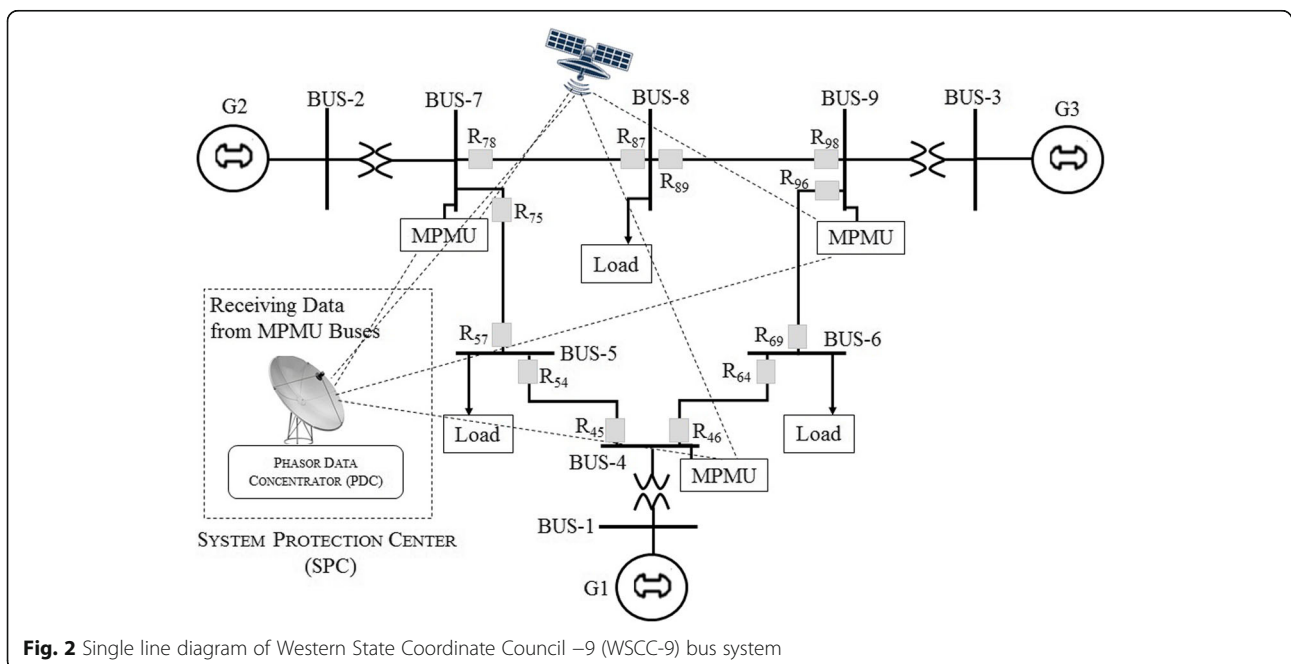
system considered are $R_1 = 2.34\,\Omega$, $R_0 = 38.85\,\Omega$, $L_1 = 95.10$ mH, $L_0 = 325.08$ mH, $C_1 = 1.24$ μF, $C_0 = 0.845$ μF [24]. The values of negative sequence parameters are same as positive sequence parameters. The simulations are carried out in per unit (p.u) system with the base kV and MVA as 400 kV and 100MVA respectively. MPMUs are installed at BUS-4, BUS-9 and BUS-7 using the optimal PMU location technique proposed for WABP in [29].

3.1.1 Dependability attribute of proposed methodology

Dependability attribute of the protection system is a measure of certainty that the protection system would function accordingly for which it is designed to operate [6].

The dependability feature of the proposed backup protection system for transmission line protection is discussed as follows.

As shown in Fig. 3, the estimated multi-phasor current components are sent to PDC in SPC. Fault detection,
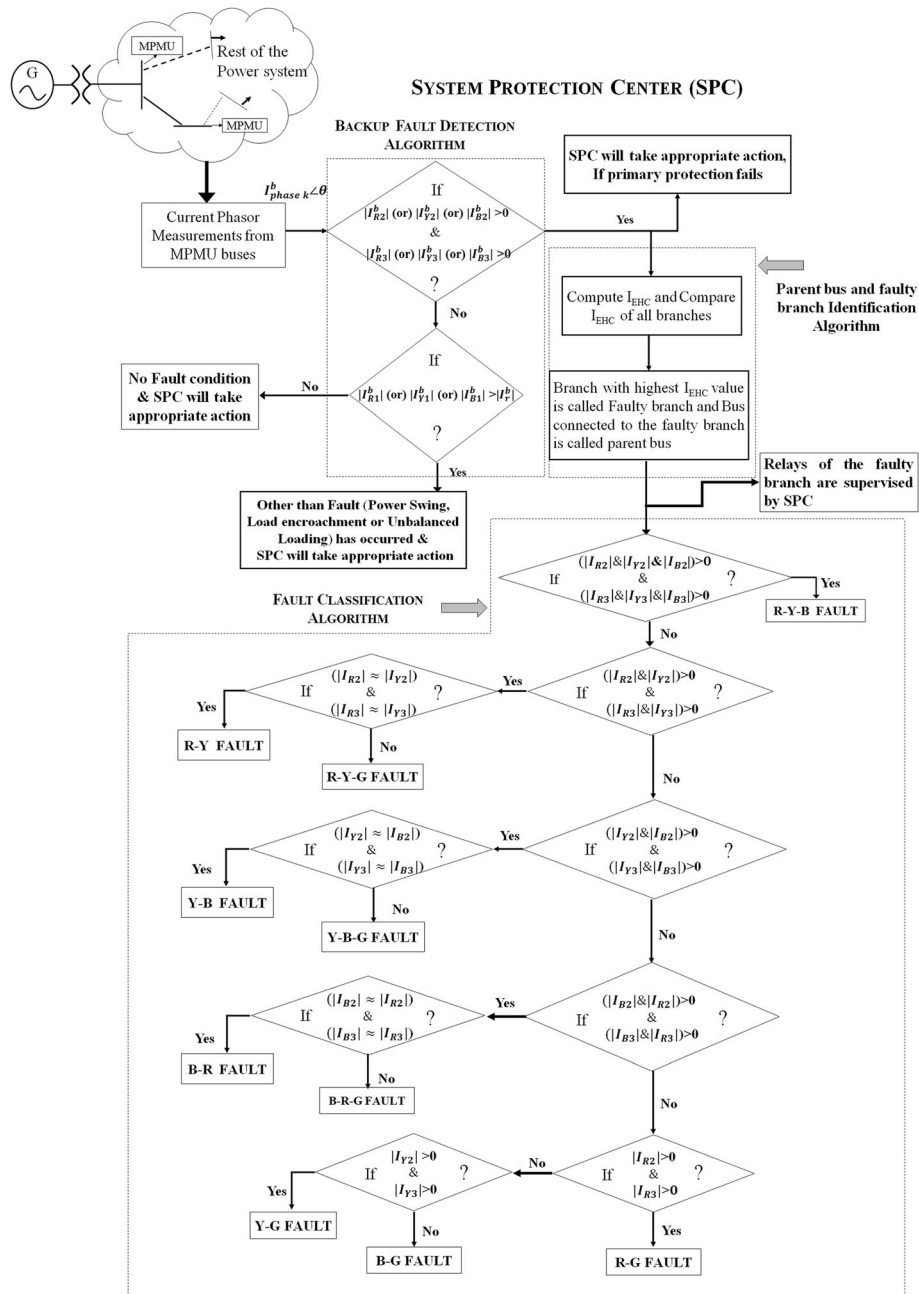
Fig. 3 Sequence of execution of proposed ASWABP Scheme at SPC

parent bus identification, fault classification, determination of the faulty branch and its relays to be supervised are obtained using ASWABP scheme in SPC. The functional logic of proposed ASWABP scheme for achieving these operations are also illustrated in Fig. 3. The three-phase current signals (R, Y & B) are passed through MPMU to estimate the fundamental (I_{R1}^b, I_{Y1}^b & I_{B1}^b), second (I_{R2}^b, I_{Y2}^b & I_{B2}^b) and third (I_{R3}^b, I_{Y3}^b & I_{B3}^b) order frequency current phasors of a branch 'b' connected to MPMU placed bus. The 2nd ($|I_{R2}^b|$, $|I_{Y2}^b|$ & $|I_{B2}^b|$) and 3rd ($|I_{R3}^b|$, $|I_{Y3}^b|$ & $|I_{B3}^b|$) order harmonic phasors of three-phase current signals are employed to detect the state of the system. During normal condition and stressed conditions the magnitudes of the second and third order current harmonic phasors are zero. However, during fault conditions, the magnitudes of second and third order current harmonic phasors are non zero.

Once the fault is detected, the next stage is identification of parent bus and faulty branch. The bus connected to the faulty branch where MPMU located is termed as the parent bus. The faulty branch will have the highest value of I_{EHC} among all branches. Hence, the faulty branch is detected and relays connected to the faulty branch to be supervised are identified. This enhances the dependability attribute of power system protection. The EHC of a particular branch in the system is calculated using Eq. (5),

$$I_{EHC} = \sqrt{\sum_{k=2,3}\left(I_{Rk}^b\right)^2 + \sum_{k=2,3}\left(I_{Yk}^b\right)^2 + \sum_{k=2,3}\left(I_{Bk}^b\right)^2} \qquad (5)$$

where I_{Rk}^b is the kth order harmonic phasor in R-phase current of a branch 'b'. Similarly, I_{Yk}^b and I_{Bk}^b represent the kth order harmonic phasors in Y and B phase currents of the branch bus 'b' respectively.

Once the parent bus is identified and the faulty branch is detected then fault classification algorithm is executed as illustrated in Fig. 3. If the magnitudes of all 2nd (I_{R2}, I_{Y2}, and I_{B2}) and 3rd (I_{R3}, I_{Y3} and I_{B3}) order harmonic phasors of three phase currents (R, Y and B) are greater than zero, identified fault is RYB. Else, if the magnitudes of predominant harmonic phasors of R and Y phase currents are greater than zero, identified fault is either RY or RYG. The type of fault is further distinguished in the following way: if $|I_{R2}|$ is equal to $|I_{Y2}|$, and $|I_{R3}|$ is equal to $|I_{Y3}|$, the classified fault is RY. Otherwise, it is RYG fault. The detected fault is either YB or YBG if the magnitudes of a second (I_{Y2} and I_{B2}) and third order harmonic phasors (I_{Y3} and I_{B3}) of Y and B phase currents are greater than zero. Further, it is classified as YB if $|I_{Y2}| \approx |I_{B2}|$, and $|I_{Y3}| \approx |I_{B3}|$. Otherwise, it is YBG fault. The identified fault is either BR or BRG if ($|I_{B2}|$ & $|I_{R2}|$) and ($|I_{B3}|$ & $|I_{R3}|$) are greater than zero. Furthermore, it

is classified as a BR fault, if $|I_{B2}| \approx |I_{R2}|$, and $|I_{B3}| \approx |I_{R3}|$. Otherwise, it is identified as a BRG fault. Detected fault will be RG if the magnitudes of predominant harmonic phasors (I_{R2} and I_{R3}) of R-phase current alone are greater than zero. Else the fault is YG if 2nd ($|I_{Y2}|$) and 3rd ($|I_{Y3}|$) order phasors of Y-phase current are higher than zero. Otherwise, the fault is BG.

Case studies are carried out with different faults with various fault conditions for validating the dependability attribute of the proposed ASWABP scheme in the WSCC-9 bus system. Results of the case studies are given in Table 1. For instance, from Table 1, when a line to line (L-L) fault in branch 9–8 with FR of 0 Ω and FIA of 0^0 at 50 km from BUS-9 occurs, the magnitude of 2nd and 3rd order harmonic current phasor estimates of almost all branches of MPMU buses are higher than zero. Hence, a fault is detected. After fault detection, EHC of all branches at MPMU buses is calculated and tabulated. From these results, it is observed that branch (9–8) has higher I_{EHC} value as compared with that of all other branches. Hence, the branch (9–8) is the faulty branch. Branch 9–8 is connected between BUS-9 and BUS-8 since MPMU is connected to BUS-9, it is considered as the parent bus. The relays of the faulty branch 9–8, R_{98} & R_{89} are supervised by SPC. Simultaneously, the fault classification algorithm is executed on $|I_{R2}|$, $|I_{Y2}|$, $|I_{B2}|$, $|I_{R3}|$, $|I_{Y3}|$ and $|I_{B3}|$ of branch 9–8. These harmonic current phasors hold the values as 1.081, 1.08, 0, 0.77, 0.78 and 0 respectively. The detected fault is either RY or RYG since ($|I_{R2}|$ & $|I_{Y2}|$) and ($|I_{R3}|$ &$|I_{Y3}|$) are higher than zero. Further, the fault is distinguished as RY because of $|I_{R2}| \approx |I_{Y2}|$ and $|I_{R3}| \approx |I_{Y3}|$. Likewise, the proposed backup fault detection, parent bus identification, relays of the faulty branch to be supervised along with classification algorithms are performed well for all LG, LLL, LLG with different fault conditions as portrayed in Table 1. Also, the performance of ASWABP scheme under no fault condition is observed and tabulated in Table 1 . It is observed from the table that under No fault condition, the magnitudes of second and third order harmonic phasors currents are zero.

From the above case studies, it is observed that the proposed methodology is instrumental in enhancing the dependability of the protection system.

3.1.2 Security attribute of proposed methodology

When transmission system is under stressed condition (like power swing, load encroachment and unbalanced loading, etc.), the insecure operation of protection system would result in greater damage to the system. In such conditions, it is desirable to alter the bias of the protection system in favor of increased security with a slightly increased possibility that the primary protection would not work as designed in case of a fault. So,

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Table 1 Results of case studies, various faults with different fault conditions, conducted on WSCC-9 bus system

Fault condition	Bus number where MPMU is installed	Connected branches with MPMU installed bus	Measurements of phasor currents from MPMU connected branch			Is fault detected? $((|I_{R2}| \& |I_{R3}|)$ or $(|I_{Y2}| \& |I_{Y3}|)$ or $(|I_{B2}| \& |I_{B3}|)) > 0$ (Y/N)	$|I_{EHC}|$	Parent bus, Faulty branch between two buses	Relays to be supervised	Fault type classified
			$|I_{R1}|, |I_{R2}|, |I_{R3}|$	$|I_{Y1}|, |I_{Y2}|, |I_{Y3}|$	$|I_{B1}|, |I_{B2}|, |I_{B3}|$					
L-G fault in branch 4–5 with FR = 100Ω, and FIA = 72^0 at 80 km from BUS-4	4	4-5	3.23, 0.89, 0.41	1.23, 0, 0	1.26, 0, 0	Y	0.993	BUS-4, Branch 4-5	R_{45} & R_{54}	RG
		4-6	3.56, 0.09, 0.063	3.98, 0, 0	4.03, 0, 0		0.108			
	7	7-5	4.09, 0.423, 0.34	2.64, 0, 0	2.68, 0, 0		0.54			
		7-8	1.71, 0.114, 0.09	2.15, 0, 0	2.18, 0, 0		0.145			
	9	9-8	0.26, 0.05, 0.04	0.24, 0, 0	0.19, 0, 0		0.064			
		9-6	1.99, 0.216, 0.19	1.72, 0, 0	1.74, 0, 0		0.285			
L-L fault in branch 9–8 with FR = 0Ω and FIA = 0^0 at 50 km from BUS-9	4	4-5	0.73, 0.093, 0.07	1.79, 0.09, 0.07	1.22, 0, 0	Y	0.161	BUS-9, Branch 9-8	R_{98} & R_{89}	RY
		4-6	2.97, 0.096, 0.08	2.07, 0.1, 0.08	2.55, 0, 0		0.178			
	7	7-5	5.0, 0.289, 0.217	3.27, 0.29, 0.22	2.172, 0, 0		0.511			
		7-8	10.77, 0.77, 0.19	12.2, 0.87, 0.29	3.96, 0, 0		1.209			
	9	9-8	13.8, 1.081, 0.77	13.9, 1.08, 0.78	0.244, 0, 0		1.88			
		9-6	2.41, 0.266, 0.18	3.89, 0.27, 0.18	1.67, 0, 0		0.455			
L-L-G fault in branch 4–6 with FR = 45Ω and FIA = 162^0 at 50 km from BUS-4	4	4-5	1.73, 0.276, 0.1	1.61, 0.24, 0.05	1.28, 0, 0	Y	0.382	BUS-4, Branch 4-6	R_{46} & R_{64}	RYG
		4-6	4.57, 1.399, 0.39	4.4, 1.074, 0.18	1.281, 0, 0		1.845			
	7	7-5	1.01, 0.36, 0.024	1.86, 0.32, 0.01	2.55, 0, 0		0.484			
		7-8	0.87, 0.345, 0.12	0.78, 0.3, 0.08	0.278, 0, 0		0.479			
	9	9-8	4.24, 0.36, 0.101	4.34, 0.29, 0.02	1.891, 0, 0		0.476			
		9-6	4.12, 1.044, 0.34	4.3, 0.99, 0.12	2.349, 0, 0		1.489			
L-L-L fault in branch 7–8 with FR = 60Ω and FIA = 54^0 at BUS-8	4	4-5	2.06, 0.49, 0.08	2.09, 0.28, 0.02	2.01, 0.55, 0.06	Y	0.789	BUS-7, Branch 7-8	R_{78} & R_{87}	RYB
		4-6	3.94, 0.198, 0.05	3.95, 0.11, 0.02	3.91, 0.19, 0.03		0.304			
	7	7-5	1.34, 0.55, 0.167	1.46, 0.4, 0.05	1.26, 0.67, 0.22		0.994			
		7-8	5.84, 1.89, 0.361	5.77, 1.18, 0.17	1.26, 2.19, 0.37		3.176			
	9	9-8	2.39, 0.938, 0.16	2.45, 0.58, 0.03	2.34, 1.09, 0.14		1.571			
		9-6	0.26, 0.18, 0.052	0.25, 0.15, 0.01	0.25, 0.24, 0.06		0.344			
No Fault Condition	4	4-5	1.091, 0, 0	1.091, 0, 0	1.091, 0, 0	N	---	---	---	---
		4-6	2.129, 0, 0	2.129, 0, 0	2.129, 0, 0					
	7	7-5	2.719, 0, 0	2.719, 0, 0	2.719, 0, 0					
		7-8	1.722, 0, 0	1.722, 0, 0	1.722, 0, 0					
	9	9-8	2.226, 0, 0	2.226, 0, 0	2.226, 0, 0					
		9-6	0.264, 0, 0	0.203, 0, 0	0.251, 0, 0					

security is defined as the measure of certainty that the protection system would not malfunction [6].

In this paper, the proposed scheme is devised to detect such events and take appropriate decisions under the supervision of SPC to enhance the security of the power system. Such events are detected using the fundamental phasor ($|I_{R1}^b|$, $|I_{Y1}^b|$ and $|I_{B1}^b|$) of three phase currents along with the second and third order harmonic phasors ($|I_{R2}^b|$, $|I_{Y2}^b|$, $|I_{B2}^b|$, $|I_{R3}^b|$, $|I_{Y3}^b|$ and $|I_{B3}^b|$) of connected branch 'b' as shown in Fig. 3. If any conditions like power swing, load encroachment, and unbalanced

loading occurs, the magnitude of 2nd and 3rd order harmonic current phasors are equal to zero but the magnitude of any one of the fundamental phasors of three phase currents will be more than the rated value. If this condition is detected SPC takes the necessary action. Thereby, the security of the protection system will be enhanced.

For illustrating the security attribute of the proposed scheme power swing, load encroachment and unbalanced loading scenarios are simulated on the WSCC-9 bus system. Case studies on power swing, load

Table 2 Results of case studies, power system contingencies without and with fault conditions, conducted on WSCC-9 bus system

Power System Condition	Bus number where MPMU is installed	Connected branches with MPMU installed bus	Measurements of phasor currents from MPMU connected branch			Is fault detected? $((|I_{R2}|\&|I_{R3}|)$ or $(|I_{Y2}|\&|I_{Y3}|)$ or $(|I_{B2}|\&|I_{B3}|))>0$ (Y/N)	$|I_{EHC}|$	Is other than fault detected? $(|I_{R1}|$ or $|I_{Y1}|$ or $|I_{B1}|)>|I_r|$ (Y/N)	Parent bus, Faulty branch between two buses	Relays to be supervised	Fault type Classified
			$|I_{R1}|,|I_{R2}|,$ $|I_{R3}|$	$|I_{Y1}|,$ $|I_{Y2}|,$ $|I_{Y3}|$	$|I_{B1}|,|I_{B2}|,$ $|I_{B3}|$						
Power Swing without fault	4	4-5	1.614, 0,0	1.545, 0, 0	1.512, 0,0	N	---	Y	---, Branch 9-6	R_{96} & R_{69}	---
		4-6	0, 0, 0	0, 0, 0	0, 0, 0						
	7	7-5	0.506, 0, 0	0.47, 0, 0	0.331, 0, 0						
		7-8	2.044, 0, 0	2.097, 0, 0	2.145, 0, 0						
	9	9-8	0.482, 0, 0	0.361, 0, 0	0.409, 0, 0						
		9-6	3.525, 0, 0	3.395, 0, 0	3.206, 0, 0						
Power Swing with LLL fault with FR = 100 Ω, FIA = 36^0 in branch 7–5 at 20 km from BUS-7	4	4-5	2.492, 0.312, 0.115	2.274, 0.422, 0.147	2.204, 0.303, 0.216	Y	0.669	---	BUS-7, Branch 7-5	R_{75} & R_{57}	RYB
		4-6	0, 0, 0	0, 0, 0	0, 0, 0		0				
	7	7-5	7.149, 0.352, 0.411	6.171, 1.086, 0.759	5.912, 1.296, 0.949		2.151				
		7-8	1.191, 0.38, 0.01	1.61, 0.424, 0.144	1.555, 0.214, 0.104		0.634				
	9	9-8	0.264, 0.06, 0.019	0.203, 0.074, 0.054	0.251, 0.075, 0.055		0.145				
		9-6	2.431, 0.138, 0.151	2.22, 0.313, 0.112	2.02, 0.419, 0.291		0.642				
Load encroachment without fault	4	4-5	0.943, 0, 0	0.92, 0, 0	0.969, 0, 0	N	---	Y	---, Branch 7-8	R_{78} & R_{87}	---
		4-6	0.389, 0, 0	0.713, 0, 0	0.516, 0, 0						
	7	7-5	2.055, 0, 0	1.949, 0, 0	2.029, 0, 0						
		7-8	5.335, 0, 0	5.804, 0, 0	5.346, 0, 0						
	9	9-8	2.85, 0,0	2.886, 0, 0	2.84, 0, 0						
		9-6	1.876, 0, 0	1.926, 0, 0	1.868, 0, 0						
Load encroachment with LLL fault with FR = 50 Ω, FIA = 0^0 at 15 km from BUS-7	4	4-5	2.769, 0.354, 0.304	2.718, 0.112, 0.068	2.264, 0.459, 0.346	Y	0.752	---	BUS-7, Branch 7-8	R_{78} & R_{87}	RYB
		4-6	3.724, 0.414, 0.346	3.558, 0.16, 0.08	3.102, 0.571, 0.409		0.903				
	7	7-5	0.776, 0.262, 0.231	1.222, 0.225, 0.186	1.194, 0.482, 0.406		0.777				
		7-8	9.745, 0.949, 0.816	9.875, 0.407, 0.322	8.391, 1.359, 1.144		2.234				

Table 2 Results of case studies, power system contingencies without and with fault conditions, conducted on WSCC-9 bus system *(Continued)*

	9	9-8	6.026, 0.859, 0.17	7.153, 0.369, 0.19	6.512, 0.793, 0.228		1.273				
		9-6	1.365, 0.125, 0.132	2.0, 0.089, 0.062	1.82, 0.195, 0.159		0.329				
Unbalanced loading	4	4-5	1.492, 0, 0	1.274, 0, 0	1.2, 0, 0	N	---	Y	---, Branch 7-8	R_{78} & R_{87}	---
		4-6	2.891, 0, 0	2.844, 0, 0	2.831, 0, 0						
	7	7-5	1.19, 0, 0	1.61, 0, 0	1.555, 0, 0						
		7-8	4.149, 0, 0	2.171, 0, 0	3.912, 0, 0						
	9	9-8	2.431, 0, 0	2.22, 0, 0	2.021, 0, 0						
		9-6	0.342, 0, 0	0.342, 0, 0	0.342, 0, 0						

encroachment with and without faults along with unbalanced loading are given in Table 2.

For instance, consider power swing condition when branch 4–6 is disconnected from the system due to some abnormal condition. The measurements of all branches connected to all MPMU buses are given in Table 2. From Table 2, the magnitude of fundamental phasors of 3-Φ current signals ($|I_{R1}^b|$, $|I_{Y1}^b|$, $|I_{B1}^b|$) of all branches of MPMU buses are higher than rated value. However, the magnitudes of the predominant current harmonic phasors ($|I_{R2}^b|$, $|I_{Y2}^b|$, $|I_{B2}^b|$, $|I_{R3}^b|$, $|I_{Y3}^b|$ and $|I_{B3}^b|$) are zero. When these values are passed through the proposed scheme, it is identified as other than fault condition because none of the second and third order harmonic current phasors satisfy the fault detection criterion, and the magnitudes of the fundamental current phasors are more than the rated values. Among all branches of MPMU buses, branch 9–6 of BUS-9 has higher magnitudes of fundamental current phasors, hence the relays $\mathbf{R_{96}}$ and $\mathbf{R_{69}}$ of the branch 6–9 are instructed (by SPC) not to operate. Similarly, the proposed algorithm can perform well even under load encroachment and unbalanced conditions as given in Table 2. The corresponding results tabulated in Table 2, validate the security attribute of the proposed algorithm. Hence, the proposed algorithm can enhance the security of the protection system.

Further, fault conditions during power swing and load encroachment are also studied, and the presence of harmonics can be observed. Results of these case studies are also tabulated in Table 2. The fault detection, parent bus identification, determination of faulty branch relays to be supervised and fault classification methods remain same as described in the preceding section. Similar analysis can be carried as illustrated in the algorithm, for all other case studies (LG, LL and LLL) and faults are classified even during power system contingencies.

From the above discussions on backup fault detection, parent bus identification, determination of the faulty branch, classification of faults and detection of power system contingencies, it is inferred that the SPC takes an appropriate decision for enhancing the security and dependability attributes of the protection system using wide-area current phasor measurements. In other words, the reliability of the protection system can be enhanced.

4 Results and discussions

In general practice, for the traditional backup protection of long transmission lines, conventional distance relays are employed with over-reaching zones [30]. These relay take local measurements for decision making and do not consider fault resistance. Moreover, their characteristics may not be adjustable to changing power system conditions [31, 32]. Hence, they are very prone to maloperate even for high impedance faults and power system contingency conditions. In this section, performance of the proposed scheme and distance protection (Mho relays) under various power system disturbances is studied on the IEEE-14 bus system. Also, for the same case studies, a comparative analysis is carried in terms of security and dependability measures of conventional and proposed protection systems. The transmission line parameters, generator and exciter model parameters of the IEEE-14 bus system are same as WSCC-9 bus

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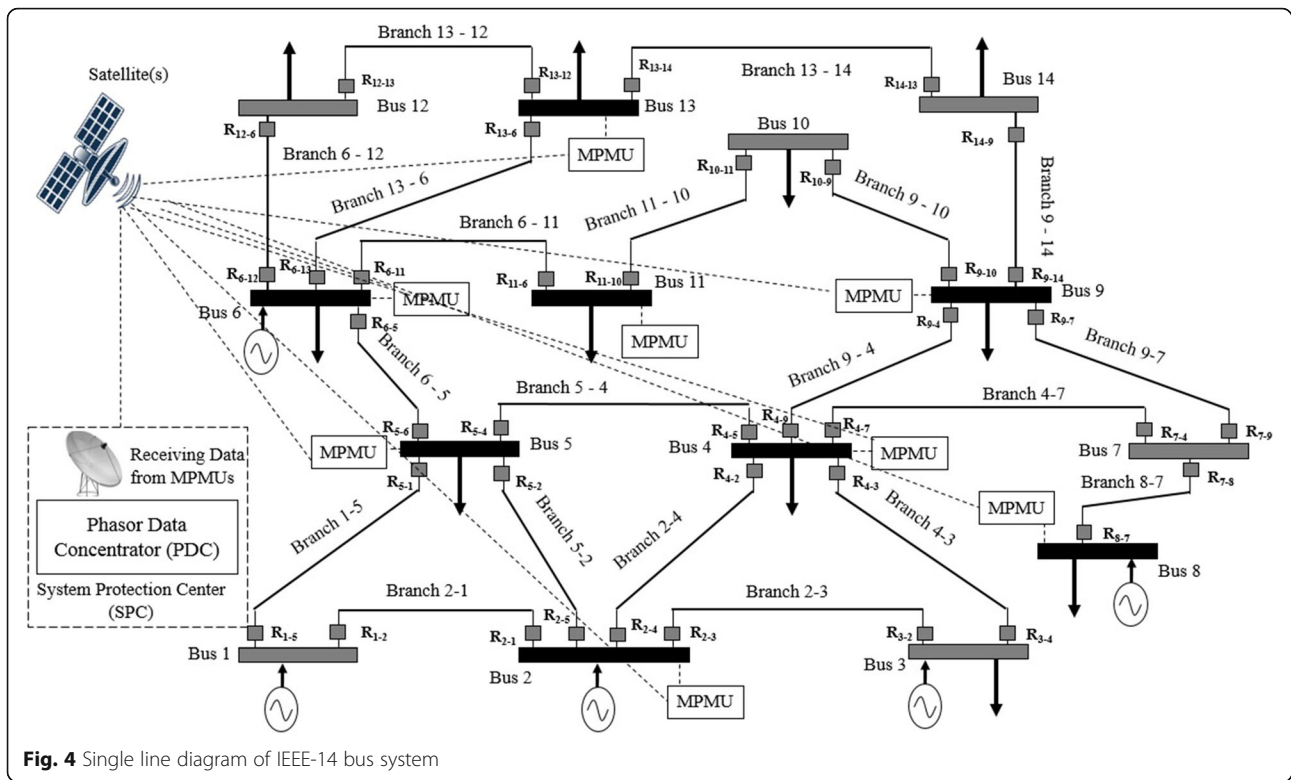
Fig. 4 Single line diagram of IEEE-14 bus system

system. MPMUs are strategically located in IEEE-14 bus system at buses 2, 4, 5, 6, 8, 9, 11 and 13 [29]. The single line diagram of the IEEE-14 bus system with MPMUs installed is shown in Fig. 4. Measurements of all branches obtained from MPMU buses are collected at SPC with the help of PDC are analyzed for power system disturbances.

4.1 The performance of the proposed ASWABP scheme during various power system disturbances

Numerous case studies on faults and power system contingencies are simulated on the IEEE-14 bus system. In this subsection, a few case studies are presented and analyzed. For better clarity, the branch measurements with significant magnitudes of fundamental, second and third order harmonic phasors of three-phase current signals are tabulated in Tables 3 and 4.

Table 3 portrays the results of different faults with different fault conditions along with no fault condition. From Table 3, it is observed that all faults are properly detected, the corresponding parent bus is identified, relays of the faulty branch are identified and type of fault is classified. The corresponding measurements are processed through the proposed algorithm as illustrated in section 3. Further, case studies of power system contingencies (power swing and load encroachment with and without faults and

unbalanced loading) conducted on IEEE-14 bus system are given in Table 4. It is observed from Table 4 that during these contingencies without fault, the magnitudes of second and third order harmonic current phasors are equal to zero, but that of fundamental current phasors are greater than the rated values. Hence, the proposed scheme has detected them as other than fault (power system contingency) events. The proposed scheme has performed as well when a fault occurs during power system contingency conditions as given in Table 4. In all the power system disturbances, SPC takes appropriate decision and guides the corresponding relays as given Tables 3 and 4.

4.2 The performance of the distance protection (Mho relays) scheme during various power system disturbances

The impedance trajectories of the distance relay for the case studies (for IEEE-14 bus system) as given in Tables 3 and 4, are shown in Figs. 5 and 6. When an LG fault occurred in branch 13–12, (with fault conditions as given in Table 3) the relay, R_{13-12} must observe the impedance in Zone-2 as per its settings, however, due to high fault impedance the fault point has not entered any of the zones as shown in Fig. 5a. Thus, the relay R_{13-12} located at branch 13–12 is unable to operate as per settings. Similarly, for double

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Table 3 Results of case studies conducted on IEEE-14 bus system under various transmission line faults

Fault condition	Bus number where MPMU is installed	Connected branches with MPMU installed bus	Measurements of phasor currents from MPMU connected branch			Is fault detected? $((\|I_{R2}\|\&\|I_{R3}\|)$ or $(\|I_{Y2}\|\&\|I_{Y3}\|)$ or $(\|I_{B2}\|\&\|I_{B3}\|))>0$ (Y/N)	$\|I_{EHC}\|$	Parent bus, Faulty branch between two buses	Relays to be supervised	Fault type classified
			$\|I_{R1}\|$, $\|I_{R2}\|$, $\|I_{R3}\|$	$\|I_{Y1}\|$, $\|I_{Y2}\|$, $\|I_{Y3}\|$	$\|I_{B1}\|$, $\|I_{B2}\|$, $\|I_{B3}\|$					
LG fault with FR of 70Ω & FIA of 144⁰ at 200 km in branch 13–12 from BUS-13	2	2-5	1.413, 0, 0	1.66, 0, 0	1.27,0.52, 0.13	Y	0.558	BUS-6, Branch 13-12	R_{13-12} & R_{12-13}	BG
	4	4-5	1.279, 0, 0	1.34, 0, 0	1.12,0.57, 0.26		0.631			
	6	6-13	0.48, 0, 0	0.41, 0, 0	1.56,0.55, 0.16		0.573			
		6-12	0.66, 0, 0	0.136, 0, 0	1.25, 0.67, 0.13		0.74			
	8	8-9	0.38, 0, 0	0.29, 0, 0	0.34, 0.026, 0.02		0.043			
	9	9-14	0.67, 0, 0	0.59, 0, 0	1.98,0.6, 0.28		0.67			
	11	11-6	0.66, 0, 0	0.84, 0, 0	0.57, 0.083, 0.19		0.22			
	13	13-12	0.15, 0, 0	2.28, 0, 0	0.2, 1.092, 0.36		1.183			
L-L fault with FR of 50Ω & FIA of 90⁰ at 0 km in branch 7-8 from BUS-7	2	2-4	0.518, 0, 0	0.42, 0.05, 0.01	0.29, 0.07, 0.04	Y	0.1	BUS-8, Branch 8-7	R_{8-7} & R_{7-8}	YB
	4	4-7	2.73, 0, 0	3.98, 1.24, 0.12	3.18, 1.72, 0.63		2.22			
	5	5-4	1.41, 0, 0	1.12, 0.561, 0.05	1.32, 0.806, 0.19		1.014			
	6	6-5	0.73, 0, 0	0.59, 0.112, 0.07	1.23, 0.835, 0.14		1.016			
	8	8-7	3.57, 0, 0	2.54, 1.64, 0.85	2.48, 1.7, 0.88		2.35			
	9	9-7	0.23, 0, 0	1.19, 0.87, 0.22	1.59, 0.97, 0.75		1.52			
	11	11-9	0.64, 0, 0	0.77, 0.14, 0.01	0.63, 0.287, 0.05		0.327			
	13	13-14	0.62, 0, 0	0.39, 0.301, 0.09	0.472,0.296, 0.28		0.517			
L-L-G fault with FR of 15Ω & FIA of 72⁰ at 45 km in branch 1–2 from BUS-2	2	2-1	0.32, 0, 0	8.25, 3.87, 0.98	9.65, 6.75, 2.09	Y	8.11	BUS-2, Branch 2-1	R_{2-1} & R_{1-2}	YBG
	4	4-5	1.19, 0, 0	1.08, 0.576,0.222	2.87,1.041, 0.270		1.3			
	5	5-1	1.74, 0, 0	5.27, 1.7, 0.2	4.7, 2.8, 0.6		3.3			
	6	6-5	0.128, 0, 0	0.11, 0, 0.01	1.65, 0.1, 0.2		0.3			
	8	8-7	0.36, 0, 0	0.33, 0.022,0.009	0.28, 0.066, 0.02		0.075			
	9	9-4	1.46, 0, 0	1.42, 0.28, 0.23	1.07, 0.543, 0.32		0.739			
	11	11-6	0.59, 0, 0	0.55, 0.03, 0.08	0.54, 0.07, 0.16		0.21			
	13	13-6	0.29, 0, 0	0.56, 0.18, 0.04	0.32, 0.11, 0.07		0.37			
L-L-L Fault with FR of 60Ω & FIA of 0⁰ at 65 km in branch 9–10 from BUS-9	2	2-5	1.59,0.245,0.191	1.6, 0.11, 0.049	1.6, 0.258, 0.223	Y	0.476	BUS-9, Branch 9-1	R_{9-10} & R_{10-9}	RYB
	4	4-9	2.87, 1.532, 0.31	2.79, 0.842, 0.05	1.86, 0.269, 0.34		1.828			
	5	5-6	3.04, 1.057, 0.279	3, 0.547,0.095	3, 1.073, 0.34		1.664			

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Table 3 Results of case studies conducted on IEEE-14 bus system under various transmission line faults *(Continued)*

	6	6-11	3.93, 1.532, 0.31	1.73, 0.842, 0.05	2.97 1.551, 0.34		2.382			
	8	8-7	0.29, 0.054, 0.03	0.32, 0.037,0.005	0.99,0.054,0.034		0.097			
	9	9-10	3.49, 1.799, 0.199	3.37, 0.981, 0.19	3.57, 1.807, 0.2		2.746			
	11	11-10	2.64, 1.647, 0.155	1.53, 0.92, 0.013	2.89 1.709, 0.148		2.554			
	13	13-14	2.16, 1.065, 0.584	2.04, 0.599,0.017	2.19,1.143, 0.686		1.901			
No Fault Condition	2	2-1	0.28, 0, 0	0.279, 0, 0	0.272, 0, 0	N	—	—	—	—
	4	4.5	1.15, 0, 0	1.149, 0, 0	1.151, 0, 0					
	5	5-6	2.01, 0, 0	2.014, 0, 0	2.02, 0, 0					
	6	6-12	0.57, 0, 0	0.56, 0, 0	0.567, 0, 0					
	8	8-7	0.35, 0, 0	0.351, 0, 0	0.351, 0, 0					
	9	9-10	0.129, 0, 0	0.129, 0, 0	0.129, 0, 0					
	11	11-6	0.585, 0, 0	0.58, 0, 0	0.537, 0, 0					
	13	13-14	0.196, 0, 0	0.199, 0, 0	0.195, 0, 0					

line fault (LL) occurred in branch 7-8 with the fault conditions as shown in Table 3, the impedance trajectory of R_{7-8} is shown in Fig. 5b. From Fig. 5b, the relay R_{7-8} is observing fault point in Zone-2 instead of Zone-1. Hence, the R_{7-8} is operated with more delay rather than operating instantaneously.

Likewise, for LLG fault occurred in branch 1–2 with fault conditions as given in Table 3, the relay R_{2-1} is observing the fault in Zone-1, which is the correct operation. For LLL occurred in branch 9–10 with fault conditions as shown in Table 3, the relay R_{9-10} is observing in Zone-3 instead of Zone-2, because of high impedance fault. The impedance locus of the relays R_{2-1} and R_{9-10} for LLG and LLL faults are shown in Fig. 5c and 5d respectively.

Further, the performance of the distance relays is verified for power swing, load encroachment and unbalanced loading (in IEEE-14 bus system). A Stable power swing is simulated by disconnecting line 10-11. When the line 10-11 is disconnected, power flowing through line 10-11 is diverted through the remaining lines connected to BUS-11. Under this condition, the impedance locus enters Zone-2 of R_{6-11} as shown in Fig. 6a. Therefore, the relay R_{6-11} will operate as per its time setting though it should not operate.

Load encroachment is created by increasing the load at BUS-3 to 150%. At this condition, the relay R_{4-3} (backup for R_{3-2}) has observed the impedance in Zone-3 as shown in Fig. 6b. Furthermore, unbalanced loading is simulated at BUS-12 by loading R, Y and B phases unequally. For this condition, the relays R_{6-12} located at BUS-6 has observed the impedance trajectory in Zone-3 as shown in Fig. 6c.

In the same way, the performance of the conventional distance relays is verified for power swing and load encroachment with faults. The distance relays will not refuse to operate for faults under any one of the above power system contingencies.

From the above studies, it can be inferred that mho relays maloperate for high impedance faults and power system contingencies (power swing, load encroachment and unbalanced loading) without faults. These situations demand adaptive supervised backup protection systems, which are based on wide-area synchrophasor measurements.

4.3 Comparative analysis of the proposed scheme with distance protection during power system disturbances

The conventional distance protection algorithms have the following drawbacks, though they are simple and dependable. The disadvantages are reduced security and reliability, fixed adaptability and limited view on power system conditions since their function is based on local measurements. The proposed algorithm can overcome the disadvantages of conventional algorithms as discussed in this section. The only issue associated with the ASWABP scheme operation is latency in data communication from MPMU to PDC (SPC). However, it becomes an inherent advantage for the proposed scheme, since it can be employed as a backup for the existing protection system. A comparative analysis is carried between the proposed scheme and the conventional distance protection relays to quantify the security and dependability measures for the same case studies considered in preceding sections. The inferences of the case studies, simulated for both the schemes are tabulated in Table 5.

Table 4 Results of case studies conducted in IEEE-14 bus system under various power system conditions

Power System Condition		Bus number where MPMU is installed	Connected branches with MPMU installed bus	Measurements of phasor currents from MPMU connected branch			Is fault detected? $((|I_{R2}| \& |I_{R3}|)$ or $(|I_{Y2}| \& |I_{Y3}|)$ or $(|I_{B2}| \& |I_{B3}|)) > 0$ (Y/N)	$|I_{EHC}|$	Is other than fault detected? $(|I_{R1}|$ or $|I_{Y1}|$ or $|I_{B1}|) > |I_r|$ (Y/N)	Parent bus, Faulty branch between two buses	Relays to be supervised	Fault type classified
				$|I_{R1}|,$ $|I_{R2}|,$ $|I_{R3}|$	$|I_{Y1}|,$ $|I_{Y2}|,$ $|I_{Y3}|$	$|I_{B1}|,$ $|I_{B2}|,$ $|I_{B3}|$						
Power Swing	Without fault	2	2-5	0.28, 0, 0	0.28, 0, 0	0.29, 0, 0	N	—	Y	—, Branch 6-11	R_{6-11} & R_{11-6}	—
		4	4-5	0.27, 0, 0	0.28, 0, 0	0.25, 0, 0						
		6	6-11	1.7, 0, 0	1.69, 0, 0	1.68, 0, 0						
			6-13	0.57, 0, 0	0.57, 0, 0	0.57, 0, 0						
			6-5	0.6, 0, 0	0.6, 0, 0	0.6, 0, 0						
		8	8-7	0.52, 0, 0	0.51, 0, 0	0.54, 0, 0						
		13	13-14	0.58, 0, 0	0.58, 0, 0	0.58, 0, 0						
			13-12	0.284, 0, 0	0.284, 0, 0	0.284, 0, 0						
	With fault (L-L-L Fault with FR of 20Ω & FIA of 0^0 at 50 km in branch 6–11 from BUS-6)	2	2-5	0.395, 0.09, 0.05	0.375, 0.078, 0.017	0.233, 0.166, 0.142	Y	0.263	—	BUS-6, Branch 6-11	R_{6-11} & R_{11-6}	RYB
		4	4-5	3.829, 0.623, 0.485	3.743, 0.056, 0.096	2.007, 0.1226, 0.563		0.984				
		6	6-5	3.432, 0.548, 0.44	3.264, 0.123, 0.17	2.598, 0.66, 0.598		1.154				
			6-11	4.82, 0.809, 0.641	4.579, 0.187, 0.216	3.559, 0.968, 0.824		1.662				
		8	8-7	0.282, 0.012, 0.009	0.268, 0.017, 0.027	0.267, 0.022, 0.036		0.055				
		9	9-10	3.829, 0.623, 0.485	3.743, 0.056, 0.096	2.92, 0.66, 0.563		1.178				
		11	11-6	4.755, 0.837, 0.61	4.78, 0.148, 0.224	3.555, 0.913, 0.617		1.535				
		13	13-6	4.823, 0.741, 0.584	4.614, 0.07, 0.039	3.713, 0.869, 0.792		1.51				
Load Encroachment	Without fault	2	2-4	0.28, 0, 0	0.3, 0, 0	0.28, 0, 0	N	—	Y	—, Branch 4-3	R_{4-3} & R_{3-4}	—
		4	4-3	2.38, 0, 0	2.4, 0, 0	2.38, 0, 0						
		5	5-4	0.646, 0, 0	0.646, 0, 0	0.643, 0, 0						
		6	6-5	0.59, 0, 0	0.58, 0, 0	0.58, 0, 0						
		8	8-7	0.35, 0, 0	0.35, 0, 0	0.35, 0, 0						
		9	9-4	1.43, 0, 0	1.43, 0, 0	1.44, 0, 0						

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**Table 4** Results of case studies conducted in IEEE-14 bus system under various power system conditions *(Continued)*

	11	11-10	0.585, 0, 0	0.585, 0, 0	0.581, 0, 0							
	13	13-14	0.298, 0, 0	0.29, 0, 0	0.29, 0, 0							
With fault (L-L-L Fault with FR of 25 Ω & FIA of 20^0 at 20 km in branch 4–9 from BUS-4)	2	2-5	1.286, 0.091, 0.061	1.293, 0.204, 0.236	1.27, 0.213, 0.212	Y	0.446	—	BUS-4, Branch 4-9	R$_{9-4}$ & R$_{4-9}$	RYB
	4	4-9	4.391,1.945, 0.599	3.619, 1.947, 0.603	2.947, 1.589, 0.919		3.416				
	5	5-4	2.031, 0.417, 0.19	1.756, 0.449, 0.265	1.866, 0.514, 0.392		0.948				
	6	6-11	0.496, 0.094, 0.037	0.413, 0.126, 0.088	0.408, 0.095, 0.079		0.221				
	8	8-7	0.337, 0.013, 0.009	0.32, 0.037, 0.021	0.319, 0.036, 0.028		0.064				
	9	9-4	1.508, 0.842, 0.235	1.195, 0.784, 0.260	0.776, 1.048, 0.502		1.673				
	11	11-9	0.579, 0.083, 0.059	0.565, 0.093, 0.078	0.565, 0.131, 0.131		0.243				
	13	13-14	0.252, 0.085, 0.008	0.342, 0.099, 0.017	0.271, 0.121, 0.034		0.182				
Unbalanced loading	2	2-5	0.281, 0, 0	0.285, 0, 0	0.284, 0, 0	N	—	Y	—, Branch 6-5	R$_{6-12}$ & R$_{12-6}$	—
	4	4-5	0.279, 0, 0	0.28, 0, 0	0.278, 0, 0						
	6	6-12	1.699, 0, 0	1.701, 0, 0	2.102, 0, 0						
	13	13-6	0.569, 0, 0	0.568, 0, 0	0.5686, 0, 0						
	5	5-1	0.584, 0, 0	0.583, 0, 0	0.585, 0, 0						
	8	8-7	0.35, 0, 0	0.376, 0, 0	0.424, 0, 0						
	9	9-10	1.433, 0, 0	1.542, 0, 0	1.7, 0, 0						
	11	11-6	0.283, 0, 0	0.284, 0, 0	0.285, 0, 0						

The case studies as depicted in Table 5 illustrate the security and dependability measures of both the schemes. The actions taken by the proposed scheme are desirable and correct for all the case studies whereas that of conventional distance protection are not desirable and incorrect in some cases. For instance, consider LG fault with FR of 70Ω & FIA of 144^0 at 200 km in branch 13–12 from BUS-13 (in the IEEE-14 bus system). As illustrated in subsection 4.1 and 4.2, the decision taken by conventional distance protection is not desirable and incorrect. Whereas using proposed ASWABP scheme, the operation of the supervised protective relay will be correct and desirable.

Similarly, for the remaining case studies, it is understood that the performance of the proposed ASWABP is superior over that of the conventional distance protection. Hence, the proposed ASWABP scheme is secure and dependable. The analysis emphasizes the necessity of the proposed scheme as an adaptive supervised wide-area backup protection for distance protection.

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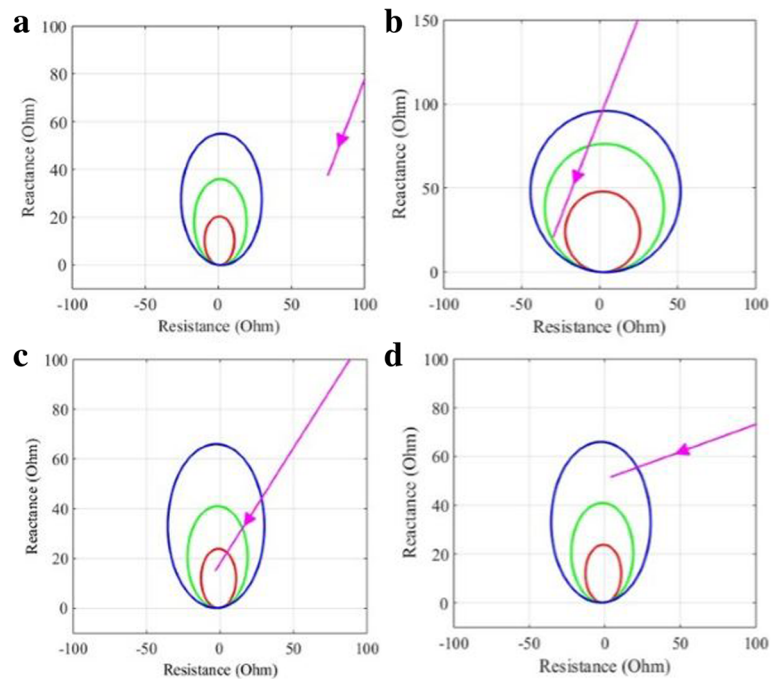
Fig. 5 Impedance trajectory of (**a**) R$_{13-12}$, when LG (70Ω, 144^0 and 200 km from BUS-13) fault occurred; (**b**) R$_{7-8}$, when LL (50Ω, 90^0 and 0 km from BUS-7) fault occurred; (**c**) R$_{2-1}$, when LLG (15Ω, 72^0 and 70 km from BUS-2) fault occurred; (**d**) R$_{9-10}$, when LLL (60Ω, 0^0 and 65 km from BUS-9) fault occurred
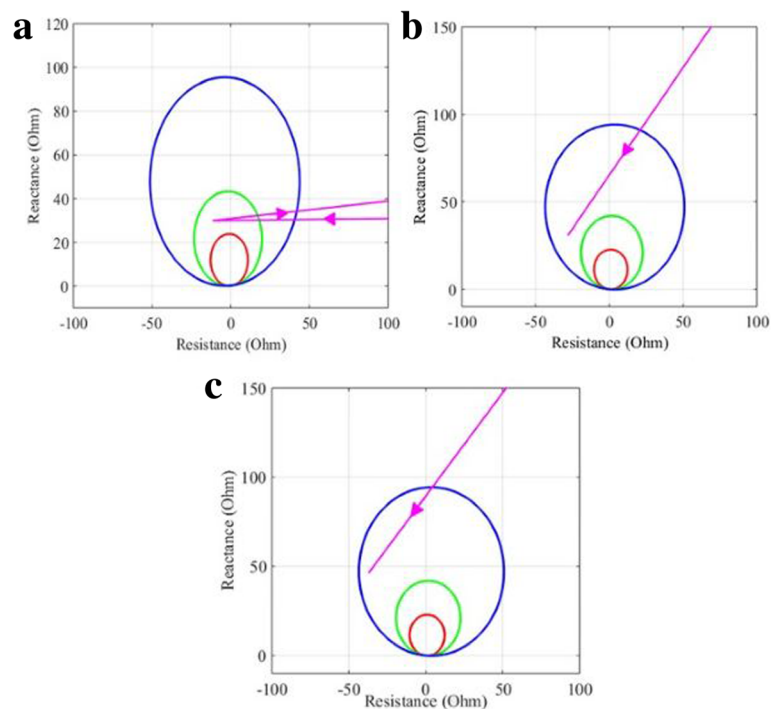
Fig. 6 Impedance trajectory of (**a**). R$_{6-11}$, when power swing occurred due to loss of line 10-11; (**b**). R$_{4-3}$, when load encroachment occurred due to overloading at BUS-3; (**c**). R$_{6-12}$, when unbalanced loading occurred at BUS-12

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Table 5 Comparative analysis of the proposed methodology with conventional distance relay during various power system disturbances in IEEE-14 bus system

Power System Disturbances	Case studies		The action taken by the proposed scheme is		The action taken by the conventional distance protection is	
			Correct (Y/N)	Desirable (Y/N)	Correct (Y/N)	Desirable (Y/N)
Fault conditions	LG (70Ω, 144^0 and 200 km in branch 13–12 from BUS-13)		Y	Y	N	N
	LL (50Ω, 180^0 and 0 km in branch 4–7 from BUS-7)		Y	Y	N	N
	LLG (15Ω, 54^0 and 70 km in branch 1–2 from BUS-2)		Y	Y	Y	Y
	LLL (60Ω, 0^0 and 65 km in branch 9–10 from BUS-9)		Y	Y	N	N
Contingency conditions	Power Swing(at BUS-6)	without fault	Y	Y	N	N
		with fault	Y	Y	Y	Y
	Load encroachment (at BUS-3)	without fault	Y	Y	N	N
		with fault	Y	Y	Y	Y
	Unbalanced loading (at BUS-12)		Y	Y	N	N

5 Conclusions

WABP systems are essential for maintaining elevated reliability of the protection system under faults and power system contingencies like power swing, load encroachment and unbalanced loading. This paper proposes MPMU based ASWABP scheme, that can detect the transmission line fault, identifies the parent bus, faulty branch & relays to be supervised and classify the type of fault during power system disturbances. WSCC-9 bus and IEEE-14 bus systems are considered as test systems. Results have shown that the proposed methodology is immune to variation in fault parameters. Also, it can achieve the security-dependability balance during faults and power system contingencies to assist system protection center (SPC) in taking appropriate decision to any catastrophic situation in case of failure in the main protection system. Comparative studies performed have validated that the proposed scheme is superior to the conventional distance protection in terms of enhanced reliability. Futhermore, comparative studies have shown the necessity of the proposed scheme as a supervised wide-area backup system for distance protection to enhance the reliability.

Authors' contributions
BM has developed and modeled the proposed ASWABP algorithm. PVV developed the Fourier analysis for fault classification methodology. SDS has made substantial contributions to simulated IEEE networks. MJBR has been technical adviser for the total work and DKM has supported us in interpreting the simulation results for fault analysis. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests

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