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PAPERS

Efficient fault identification scheme of compensated transmission grid based on correlated reactive power measurements and discrete wavelet transform

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The early fault identification in high-voltage power systems is a substantial aspect not only to minimize equipment failure but also to increase both the reliability and stability in power system. Subsequently, the aim of this paper is to propose the adaptive fault-identification scheme based on multi-resolution analysis technique. The proposed method is dependent on monitoring both voltages and currents from single-ended measuring system. The correlation among the reactive power computation and discrete wavelet transform is used to generate the significant criteria which are used to discriminate between short-circuit currents and energizing heavy loads behaviour. Different transmission network configurations are investigated to assess the dependability, security, and reliability of fault identification relay as well. The correlative protection scheme attains the accurate results under healthy disturbances, and therefore it is superior to other conventional approaches. In addition, a selective study is applied to different mother wavelets to find the best one. The response of the proposed scheme to the compensated transmission line is also verified at a wide range of compensation levels with faults before and after compensated bank. Simulation tests have been handled via ATP-EMTP to investigate the proper practicability and adaptability of the fault-identecation relay.

Keywords: compensated transmission lines, DWT, fault identification

1 Introduction

Fault detection and classification algorithms have a noticeable role to protect rise-cost and safety-critical high voltage power systems. With growing demands for electrical consumption, utilities are compelled to boost the transmission capability of electrical transmission systems. This is why immediately detection and classification process for short-circuit faults is required to protect transmission lines. In electrical power systems, there are many practical applications such as power transformers, induction motors, synchronous generators, transmission lines, and distribution systems, all these components need to bypass an abnormal event progression. Therefore, plenty of methods have been developed to deal with the fault detection issues through transmission networks. Nevertheless, these methods faced a lot of difficulties whether in discriminating heavy load switching or in recognizing a little transmission line faults [1-2]. As an illustration, in the case of heavy load switching (non-fault) occurrence, the behaviour of three phases currents and voltages may resemble a three-phase fault situation which is more likely to lead to wrong decision. Thus, conventional schemes require more developing to increase their ability to distinguish heavy load switching conditions and three-phase fault cases. In fact, the mal-operation of protective relaying systemswhich have been designed to detect, classify, identify faulty phase, and remove the fault eventsmay cause the catastrophic effects on power system networks [3]. Therefore, the accurate fault detection and classification actions must be proposed to perform the speedy recovery of the unhealthy phases and to decline the time abruption. In reality, transmission lines confront a considerable rise in electromagnetic transient signals through cables while short circuit occurrence. These phenomena constitute non-stationary signal through transmission lines in both time and frequency domains. A DWT based- multi-resolution analysis technique (MRAT) is one of the most outstanding methods to analyze these non-stationary signals in which it markedly provides detailed information about faults to protection main purpose [4]. A MRAT has the capability of capturing the relevant features of elevtrical signals and localize them in time-domain precisely. The extracted feature from measured signals aids to identify the natural of faults so that more and more attempts have been addressed in fault-identification area for either compensated and non-compensated transmission lines. To begin with non-compensated transmission lines, many studies have been introduced to detect and classify faults without using any intelligent system [5-8]. The proposed schemes used DWT to obtain and extract the salient features of

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the faulty signals. In [9-10], the merging of DWT, Singular Value Decomposition (SVD) and Shannon entropy was presented to identify fault distinctive in transmission network. Reference [11] proposed the fault identification scheme for three-terminal transmission systems via monitoring the impact of reactive power behaviour during fault condition. In [12], new terminologies in fault identification process were suggested namely, the sensitivity and stability of fault identification schemes. This study also relied on the DWT by using the hybridization among wavelet coefficients and their deviation corresponding to three-phase currents. In [13-20], other methods were suggested by using of the artificial neural-networks (ANNs) and / or expert systems. In [13], an algorithm relied on the conjunction of DWT and ANNs technique for a fault identification was addressed. In [14], a novel method was performed using hyperbolic s-transform based on radial basis function neural-network (RBFNN) for a fault classification concept. Also, in [15], a new method was derived using integrated multi-wavelet packet entropy technique with RBFNN for classifying of different fault types. In [16], a developed fault-identification algorithm relied on the combination of both DWT and Probability Neural Network (PNN) to extract the distinctive fault features was introduced. In [17], the short-circuit fault was identified via the intrinsic time decomposition technique based on the integration of Singular Value Decomposition (SVD) with PNN. In [18], a protection scheme for a tripled-circuits transmission line was proposed by using the incorporation of DWT and Deep Neural Network (DNN) in which the DNN is trained using wavelet coefficients of current signals. In [19], the performance of fault identification relay (FIR) based on the machine intelligent platform WEKA via the integration of three types of selection techniques, namely information gain, gain ratio and support vector machine (SVM) algorithms were applied to doubled-circuits transmission line. The determinant function was inferred and used to extract the salient fault features over different data windows. In [20], a method relied on SVM technique was presented. This scheme was mainly dependent on DWT to handle the important features for fault detection process. These features were then fed into SVM technique to identify the unhealthy phases. However, the negative side of ANN & expert systems are relying on huge samples and data of training for the picture of perception, which greatly defects their practical applications. Also, most studies have been unable to assimilate transmission line uncertainties that may impact on the reliability of FIR.

As for a series-compensated transmission line, a great number of FIRs suffer from the mal-operation of fault identification schemes at various conditions. As a matter of fact, the series compensator is constructed by both metal oxide varistor MOV and parallel air-gap combination to enhance voltage profile and transmission capability, but this combination results in a rise in system nonlinearity. For this reason, the series compensated transmission line configurations is not straightforward and requires advanced protection algorithms. On top of that, the most recent publications related to fault identification schemes based on both series- and shunt- compensation have been introduced in [21-26]. In [21], a review in the protection schemes regarding series compensated networks was presented. The core of this work was to delineate the most popular types of series compensation-based fault identification complexities which have been founded in power system. In [22], based on distributed parameter model, the fault location scheme was presented via monitoring unsynchronized voltage and current signals for a series- compensated line. In [23], an integrated directional relay method was presented to a series compensated line. The proposed scheme relied on the use of the measured phase angle and magnitude of the positive-sequence current and voltage, respectively. The discrimination among transient and permanent faults was introduced for transmission line including shunt compensated reactors in [24]. In [25], another reclosing scheme was presented for shunt reactor compensated systems on the basis of current spectrum analysis. In [26], an adaptive neuro-fuzzy inference system (ANFIS) was developed for fault recognition process in the presence of series compensated transmission line. It is found that most conventional FIRs in previous studies are inadequate to provide the corrective decision with a wide range of compensation levels. Also, many of them consisted of multi-stage techniques. This inevitably leads to consume more time and increase their computational burden. To redress these gaps, in this paper, a proposed adaptive fault-identification scheme (AFIS) is designed to overcome this dilemma relying on the integration of instantaneous reactive power with MRAT. Based on this integration, the proposed scheme can identify the short-circuit fault on compensated transmission network; meanwhile, the complication of discriminating among heavy load switching and short-circuit fault could be solved. The proposed scheme depends on real -time currents and voltages captured from one side of transmission line through the sliding window to compute instantaneous reactive power which processed via DWT to extract fault criteria. As a result, the proposed AFIS -based the wavelet coefficients relied on the reactive power behaviour during disturbance that provides faster and more accurate fault-identification action than well-known wavelet coefficients based only on voltages or currents as reported in previous works. A 6.4-kHZ sampling rate and db6 mother wavelet are selected to make a little of computational attempts. The performance of the proposed method is tested and evaluated under different healthy and unhealthy disturbances with different short-circuit parameters. In addition, both dependability and security concepts would be discussed to evaluate the performance of AFIS. Using the integrating of ATP-EMTP and MATLAB simulators, the results are presented to illustrate the potential benefits of the proposed AFIS.

We provide an overview of reactive power computation with the basic concepts of conventional wavelet transform. The proposed scheme of fault identification relay is

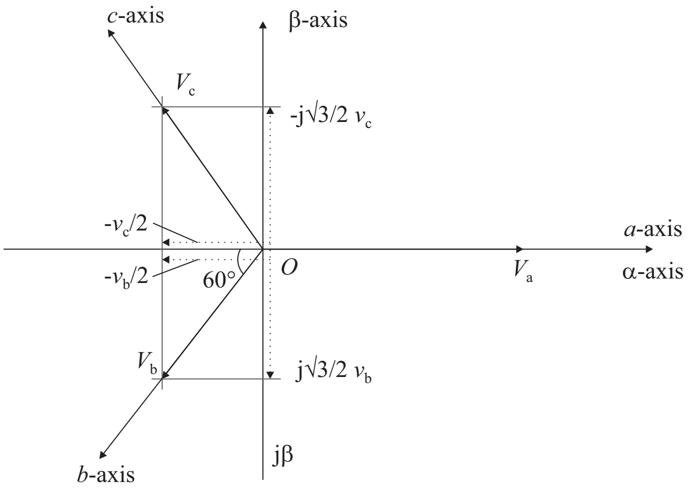

Fig. 1. The conversion of three phases coordinates ABC to α and β coordinates

presented and the tested transmission network is simulated with different fault cases. The result of fault identification scheme is discussed and its dependably factors are presented together with an assessment study of proposed scheme compared to the most closed schemes in literature.

2 Reactive power computation and DWT analysis

2.1 The instantaneous reactive power computation

The dependency of previous fault identification techniques on the currents and voltages nature is not accurate because the power system performance (e.g. load, switching) may change continuously. For this, a new approach based on the reactive power attitude is introduced in this proposed method. The application of reactive power-fault identification studies is implemented using Clarke model. It is well-known that the Clarke transformation is often applied to analyze an imbalanced grid during fault occurrence [27]. First of all, the three phase voltages and currents are converted to two orthogonal stationary axes which are denoted as α-axis and β-axis, each of them is perpendicular to each other. The Clarke transformation for three phases voltage coordinates ABC is depicted as Fig. 1.

The phase-model transformation of instantaneous voltages can be derived as follows

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}, \tag{1}$$

where v_a, v_b, v_c are, respectively, instantaneous voltage corresponding to three phases and v_α, v_β refer to stationary orthogonal of voltages, and v_0 refer to voltage ground mode, therefore,

$$v_0 = \frac{1}{\sqrt{3}}\big(v_a + v_b + v_c\big), \tag{2}$$

$$v_\alpha = \sqrt{\frac{2}{3}}\big(v_a - \frac{v_b}{2} - \frac{v_c}{2}\big), \tag{3}$$

$$v_\beta = \frac{1}{\sqrt{2}}\big(v_b - v_c\big). \tag{4}$$

Similarly, we can derive the Clarke transformation of instantaneous three phase currents i_a, i_b, and i_c, which is given below to extract i_0, i_α, and i_β.

$$\begin{bmatrix} i_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \tag{5}$$

where, i_α, i_β refer to stationary orthogonal of currents, and i_0 refers to ground current mode.

Based on Clarke transformation, the instantaneous reactive power $q(t)$ is computed as the cross product of two mutual perpendicular quantities as mentioned in [27]. The calculation of instantaneous reactive power is expressed as,

$$q(t) = v_\alpha \, i_\beta - v_\beta \, i_\alpha. \tag{6}$$

Therefore, the instantaneous reactive power measured per phase can be represented as

$$q_a(t) = \frac{1}{\sqrt{3}}\big(v_c - v_b\big)i_a, \tag{7}$$

$$q_a(t) = \frac{1}{\sqrt{3}}\big(v_a - v_c\big)i_b, \tag{8}$$

$$q_a(t) = \frac{1}{\sqrt{3}}\big(v_b - v_a\big)i_c, \tag{9}$$

where, $q_a(t)$, $q_b(t)$, and $q_c(t)$ are the measured reactive power corresponding to three phases (a,b,c) at relay point.

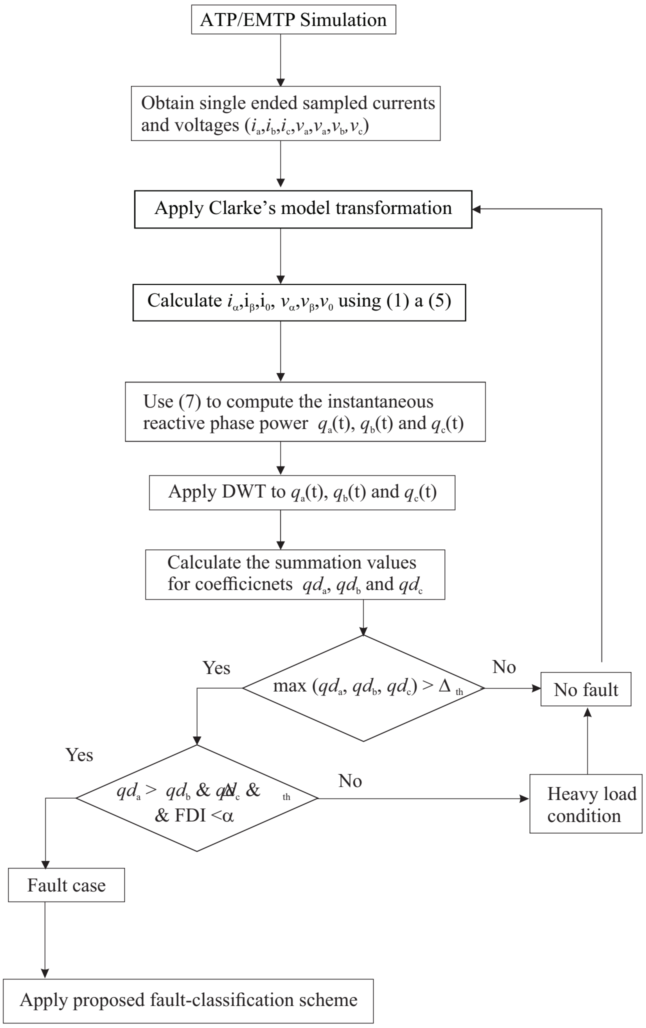

Fig. 2. Flow chart for proposed fault detection scheme

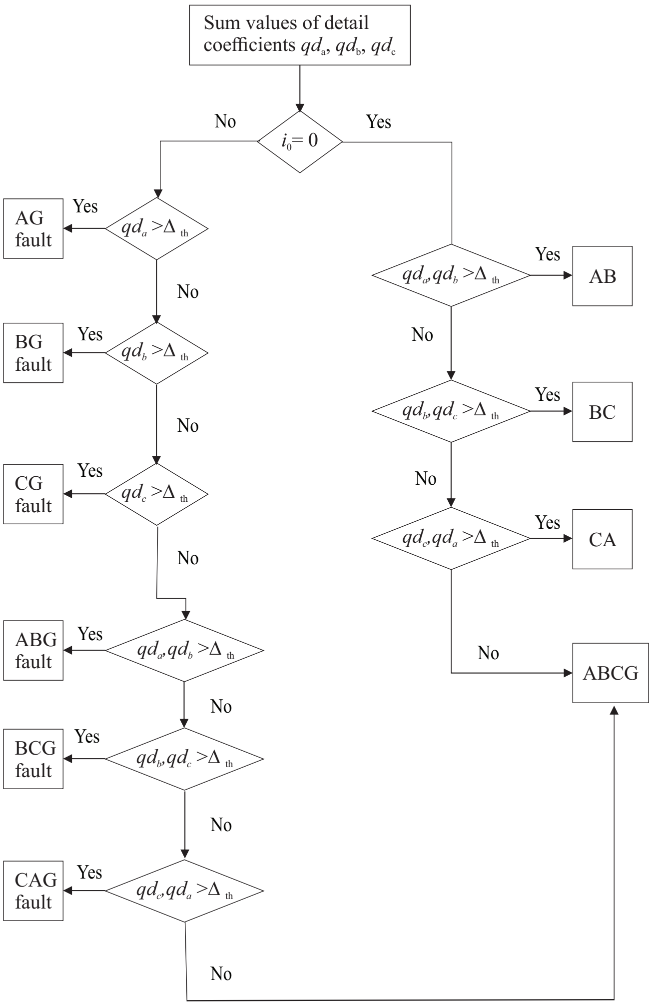

Fig. 3. Flow chart for proposed fault classification scheme

2.2 *Extraction of wavelet coefficients-based signal processing technique*

The DWT-based multi-resolution analysis technique possesses better properties than conventional DFT. The DWT has extracted more detailed information about both time and frequency domains. Wavelet technique is the most perfect decomposition tool that is used to extract the salient features of transmission line faults. Consequently, following that the instantaneous reactive power per phase is calculating, the MRAT is applied to decompose the computed reactive power signals into details and approximate coefficients. DWT is designed to give details and approximate coefficients for input signals as tree-structured filter bank as follows [28]

$$A_1[k] = \sum_{n=-\infty}^{\infty} X[n]L[n-2k], \quad D_1[k] = \sum_{n=-\infty}^{\infty} X[n]h[n-2k], \tag{10}$$

where, X is the input sampled signal, k represents the translation interval, $L(n)$ and $h(n)$ are scaling and wavelet filters. The reactive power details are relied on translating and dilating of fixed basis function, namely, mother wavelet. A basis wavelet function is defined as below, [28]

$$\Psi_{j,k}(t) = 2^{-j/2}\Psi\big(2^{-j}t - k\big). \tag{11}$$

The mother wavelet selection represents a critical aspect in fault detection and classification techniques because the high-frequency components are highly affected to mother wavelet choice. The Daubechies wavelet family is adopted in this study. As a matter of fact, it is more sensitive to sudden changes as fault and heavy load switching [29]. Therefore, the db6 is selected as mother wavelet to decompose the measured reactive power signals into high- and low-frequency components. The proposed method founds that db6 (mother wavelet) has ability to give a high performance based on reactive power measurements. Meanwhile, the sum value of details coefficients per phase (SVDCs) are computed and used as criterion for fault detection and classification scheme. Also, the details coefficient of ground current mode is used to differentiate among grounded and ungrounded faults.

3 Proposed reactive power measurements based protection scheme

In this study, the proposed AFIS relied on local voltages and currents are only captured from one-terminal measuring system. Next, three-phase voltages and currents are sampled at sampling rate ($f_{\rm s} = 6.4\,\rm kHz$) as in [6]. The Clarkes model transformation is applied to sampled signals as illustrated through (1) to (5). Subsequently, the instantaneous reactive powers per phase are calculated corresponding to (7)-(11) as mentioned in section 2. Thereafter, the MRAT combined through one-level of decomposition is presented to extract the details of reactive power. Finally, the SVDC for each phase ($qd_{\rm a}, qd_{\rm b}, qd_{\rm c}$) is used as input to the proposed protection scheme. The proposed scheme is implemented in two subsequent stages. In the first stage, the term of Fault Detection Index (FDI) based on SVDC is proposed. The FDI is designed to discriminate between fault situation and heavy load switching. In the second stage, after the fault would be discriminated, the same input data are utilized to make fault classification process.

3.1 Fault detection based reactive-power computation

The proposed fault-detection scheme is designed to be able to detect any type of shunt-fault as well as making discrimination between non-fault transient events. Due to the proposed FDI, the fault-detection scheme can overcome the major issue in the previous studies. To put it differently, most of existing studies could be detect any heavy load switching event like a symmetrical fault rather than non-fault transient event. Consequently, the proposed fault-detection scheme is designed to combat this issue. Based on indices are defined as the SVDC, the proposed scheme works with high effective and reliable operation. Generally speaking, under normal operation, the values of $qd_{\rm a}, qd_{\rm b}$, and $qd_{\rm c}$ have marginal changes. By comparing the maximum term of $qd_{\rm a}, qd_{\rm b}, qd_{\rm c}$ values with an adaptive threshold value, the heavy load switching, or transmission line fault can be detectable. With this in mind, if the maximum value of sum details per phase exceeds an adaptive threshold value (Δth) and FDI is less than a fixed threshold value (), the fault is detected. On the contrary, provided that the SVDC for all phases exceeds over the adaptive threshold value and FDI is higher than the fixed threshold value, the non-fault transient event is detected as a result the proposed scheme does not react. The proposed FDI is defined as the ratio of difference maximum and minimum sum of details per phase to median sum of details value as follows

$$FDI = \frac{\max(qd_i) - \min(qd_i)}{\operatorname{med}(qd_i)}, \quad i = \mathrm{a, b, c}. \tag{12}$$

where, qd_i sum of details per phase, min, max, and mid refer to the minimum, maximum, median values, respectively. The adaptive-threshold is defined as the logical pattern as the following formula

$$\Delta_{\rm th} = \max(qd_{\rm a}, qd_{\rm b}, qd_{\rm c})\varepsilon, \tag{13}$$

where qda, qdb, qdc are SVDC for phase A, B, and C, respectively. In this equation, the parameter $\Delta_{\rm th}$ denotes the adaptive threshold. Further, the adaptive threshold value needs to the correction index which is required to make a corrective decision that is denoted as ε. This threshold value is adaptively relied on the transmission line topologies as well as diverse loading conditions and source impedance variations. It must be mentioned that the choice of adaptive threshold value for fault detection schemes is a critical aspect. For this reason, a straightforward method named Otsu thresholding method is considered to set the adaptive threshold. Figure 2 illustrates the flow chart diagram of the presented fault-detection method based on a logical pattern using adaptive threshold and FDI.

3.2 Fault classification based reactive-power computation

After a fault detection is declared, it is a very important to identify which type of fault has taken place, once the data are reached to protective relay. The proposed reactive power- based fault classification scheme is performed using the SVDC in each phase. This criterion is used to classify between different fault types based on the proposed adaptive threshold formula as (13). In this study, the same features which have been extracted in the detection stage are also used in classification scheme. Forthwith, the fault detection is investigated, the faulty phase will be identified using another logical pattern as depicted in Fig. 3. The flowchart describes the entire features of the proposed fault-classification scheme. The classification methodology is launched using the value of $qd_{\rm a}, qd_{\rm b}, qd_{\rm c}$ and ground current mode value which is able to discriminate between grounded and ungrounded faults. For instance, during single phase to ground fault, the SVDC of faulty phase only exceeds the adaptive $\Delta_{\rm th}$, whereas double phase to ground fault, the SVDCs of faulty phases exceed the adaptive $\Delta_{\rm th}$, this means that the SVDC in faulty phase is higher than the healthy phase. For three-phase fault, the values of $qd_{\rm a}, qd_{\rm b}, qd_{\rm c}$ exceed the adaptive $\Delta_{\rm th}$ threshold value.

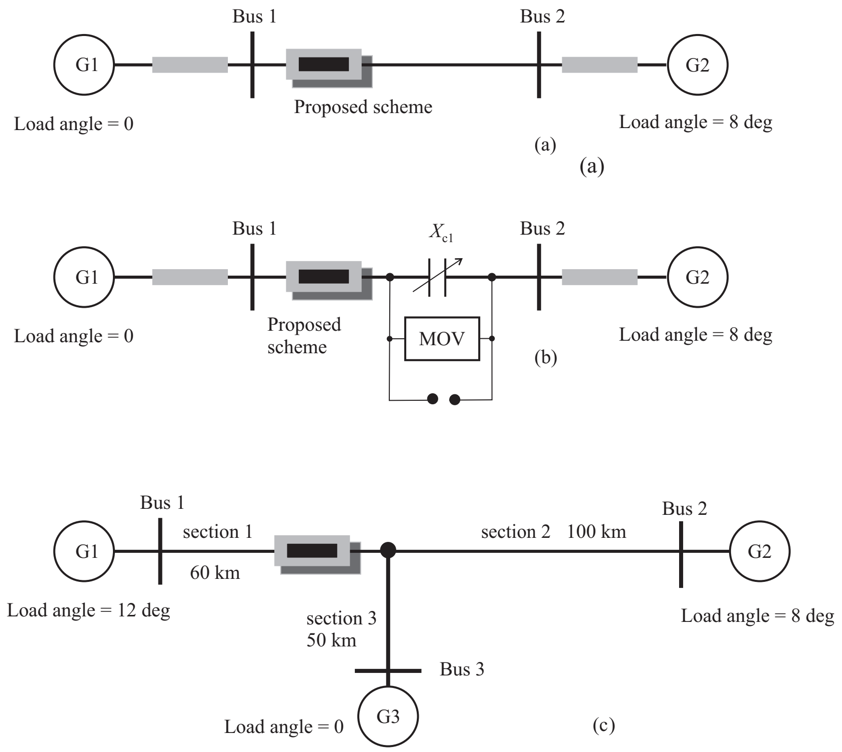

Fig. 4. Studied different transmission network configurations: (a) – uncompensated two-terminal networks, (b) – compensated two-terminal networks, and (c) – teed transmission lines

4 Applications

4.1 *Description of studied different transmission network configurations*

To check the reliability of the proposed method, different transmission network configurations have been simulated via ATP/EMTP package. The first one is a typical 500 kV uncompensated two-terminal transmission lines, 50 Hz, is used to test the proposed method performance. Two-sources are interconnected by using single overhead transmission lines and its length is 300-km as shown in Fig. 4(a). The data of the tested system for substations and transmission line are mentioned in [7]. The second one is a typical 500-kV series-compensated two-terminal transmission lines. Series-compensated line is investigated by inserting series capacitors at midpoint of a two-terminal transmission line to alleviate the impact of inductive reactance and enhance the system load ability. As depicted in Fig. 4(b), Metal oxide varistor (MOV) and air gab unit have been used to protect the series capacitor against surge high voltage during abnormal situation. The information of compensated transmission line model is taken as [23]. The last one is a typical 400-kV, 50 Hz, teed transmission lines as shown in Fig. 4(c). The teed system has three branches (sec1, sec2, and sec3) and their lengths are 60 km, 100 km, 50 km, respectively. The test transmission line parameters and sources information are provided as in [30].

4.2 *Fault simulation studies*

Several simulations studies have been verified for all studied transmission network configurations as depicted in Fig. 4. when fault occurs, voltages and currents are sampled from single end measuring system. The simulation provides sampled signals at a frequency of 6.4 kHz (128 samples /cycle) to the scheme. From ATP -EMTP simulator, all through one cycle window, sampled voltages and currents are loaded into the MATLAB program. Thereafter, the reactive powers are computed and then they are processed via MRAT, following that the fault criteria are fed into the proposed method to discriminate between fault and heavy load switching condition. Finally, the fault classification is presented to recognize the faulty phase. For this purpose, several fault cases and heavy loads switching have been tested to show the success of the proposed method.

- Single phase to ground fault (AG, BG, CG)
- Double phase to ground fault (AB-G, BC-G, CA-G)
- Double phase to phase fault (A-B, B-C, C-A)
- 3-phase fault (ABC-G)

The proposed method also has been studied at different fault parameters *eg* resistances, locations and inception angles to verify the authenticity of the proposed scheme.

Table 1. Simulation studies for selecting the convenient mother wavelet

Fault type	$R_{\rm F}$ (Ω)	$qd_{\rm a}$ $\times 10^3$	$qd_{\rm b}$ $\times 10^3$	$qd_{\rm c}$ $\times 10^3$	i_0 (A)	Fault identification Decision
			db4			
Healthy		246.3	232	248.87	0	No-fault
LG	0.001	5641.9	255	294.23	390	LG
LLG	60	1804.8	2083	298.15	174	LLG
LL	80	1908.8	2608	159.16	0	False decision
LLL	200	702.9	681	662.7	0	False decision
			db6			
Healthy		2.02	2.15	2.18	0	No-fault
LG	0.001	48.18	2.22	2.69	390	LG
LLG	60	15.91	17.72	2.56	147	LLG
LL	80	16.83	22.95	1.42	0	LL
LLL	200	6.23	5.847	5.92	0	LLL
			db8			
Healthy		0.19	0.171	0.189	0	No-fault
LG	0.001	4.75	0.208	0.393	390	LG
LLG	60	1.14	1.129	0.187	147	LLG
LL	80	1.18	1.766	0.091	0	False decision
LLL	200	0.48	0.589	0.443	0	False decision
			db10			
Healthy		0.19	0.162	0.168	0	No-fault
LG	0.001	4.58	0.206	0.295	390	LG
LLG	60	1.25	1.149	0.161	174	LLG
LL	80	1.20	1.789	0.101	0	LL
LLL	200	0.46	0.524	0.479	0	False decision

4.3 The appropriate selection for mother wavelet

Different mother wavelets have been assessed to identify the convenient mother wavelet to a practical application. The choice of beneficial mother wavelet plays a significant aspect in application of fault detection and classification. There have been more previous studies that reported in recent decades with applicable impact of wavelet / wavelet packet transform for given application. The Daubechies (db) is commonly used as basis wavelet for protection purpose. Generally, db4 mother wavelet is used as the perfect method for fault detection. At the same time, the use of db6 mother wavelet has been suggested in [4], [29], and [31]. For the purpose of picking up the most acceptable basis wavelet, different mother wavelets are addressed as shown in Tab. 1 to verify of the selection of the most dominant mother wavelet corresponding to proposed scheme. The first system as shown in Fig. 4(a) is used to appraise the proposed scheme with using db6 as the more advantageous mother wavelet.

5 Results and discussion

5.1 Assumptions

To assess the optimum fault detection and classification algorithm, the majority of studies have been done in this paper. These studies revealed that the SVDCs-based reactive power measured per phase during fault condition are higher than healthy phases. On the other hand, during healthy condition, the SVDCs-based reactive power corresponding to three phases have no significant difference between them. With this evidence, this criterion is allocated as a discriminative feature in the proposed approach. An adaptive-threshold value is estimated according to the discriminative feature during healthy case based on sliding window technique. It was tested and investigated via the proposed scheme to show how the proposed AFIS can operate correctly under different operating conditions. For practical application, any FIR scheme in general for protection purpose requires adabtive method to prevent false tripping due to non-fault transient events. The reason for this is that protection schemes always need to set threshold values. Therefore,

Table 2. The impact of series compensation on the proposed scheme and fault

Compensation percentage	Fault type	d_{F} (km)	R_{F} (Ω)	Coefficients and features					Relay decision
				qd_{a} $\times 10^3$	qd_{b} $\times 10^3$	qd_{c} $\times 10^3$	Δ_{th} $\times 10^3$	i_0 (A)	
0	Healthy			2.17	2.01	2.22	3.25	0	No-fault
	LG	50	100	15.32	2.25	2.01		129	LG fault in phase A
	LG	30	300	9.08	1.74	1.49		64.82	LG fault in phase
30	Healthy			2.19	2.20	2.19	3.21	0	No-fault
	LG	50	100	15.98	2.27	2.01		129	LG fault in phase
	LG	30	300	9.29	1.79	1.53		64.82	LG fault in phase
40	Healthy			2.18	2.08	2.20	3.20	0	No-fault
	LG	50	100	15.64	2.24	2.08		129	LG fault in phase
	LG	30	300	9.06	1.74	1.53		64.82	LG fault in phase
50	Healthy			2.17	2.05	2.18	3.19	0	No-fault
	LG	50	100	16.00	2.25	2.18		129	LG fault in phase
	LG	30	300	9.03	1.76	1.50		64.82	LG fault in phase
70	Healthy			2.14	2.05	2.16	3.14	0	No-fault
	LG	50	100	15.86	2.27	2.01		129	LG fault in phase
	LG	30	300	9.05	1.76	1.51		64.82	LG fault in phase

and could be used to identify short circuit fault. is the correction index with a range 1.09-1.2 for fault identification task, is fixed threshold value with range 0.18-0.25.

5.2 Simulation results

The response of the proposed AFIS has been tested on compensated transmission lines via series capacitor insertion at the middle of the line as shown in Fig. 4. It is well-known that the installed series-capacitor improves the power transfer capability of the line and enhances voltage profile. Furthermore, series compensation method is the way to inject the reactive power in series through the transmission line; as a result, it reduces the impedance of the line. The proposed scheme is tested under different levels of compensation as 30%, 40%, 50%, and 70%. The choice of these specific compensation levels is based on the existing studies as reported in [21, 25, 26]. Table 4 shows the performance of proposed scheme with & without series compensation capacitor under healthy and faulty conditions. For healthy case, it is observed that the slight changing in adaptive threshold value between different compensation levels during healthy cases. During fault cases, in the case of compensated transmission line, the presence will alter the effective fault impedance. So, the conventional FIRs schemes have limitations in that case. Table 2 shows the simulation results for single line to ground fault before /after compensator bank. Also, the capacitor compensation level is varied a wide range from 30% to 70%. It is cleared from several tests that the proposed scheme is able to detect and classify faults on series compensated lines correctly. To evaluate the effective of proposed scheme, diffident faults with varying resistances are simulated. Due to the increasing of fault-resistance value, the fault current may be exposed to considerable damping in its magnitude. To prove the efficacy of the proposed fault-identification scheme against this difficulty, six different values of fault-resistances ($R_F =$ 3, 6, 40, 60, 80, 100, 300 Ω) are simulated. Table 1 illustrates that the proposed scheme is immune to the effect of fault resistances in a wide range from ($R_F = 0\,\mathrm{to}\,300\,\Omega$). Therefore, the proposed scheme can be still insensitive to high fault-resistance and can give a right response for the tested transmission configuration.

6 Dependability and security of proposed AFIS

The proposed AFIS is appraised using two significant characteristics: dependability and security. Basically, Basically, it is necessary that the multifunctional AFSI provides the protective relay including the capability to achieve both dependability and security without compromising either. In this case some false tripping may happen, which can lead in the worst-case to catastrophic impact on power system. In fact, the dependability indicates to a certainty grade that AFIS will run correctly, and this term is mainly dependent on the relay sensitivity. To demonstrate the performance of proposed AFIS, the dependability and security of the proposed scheme

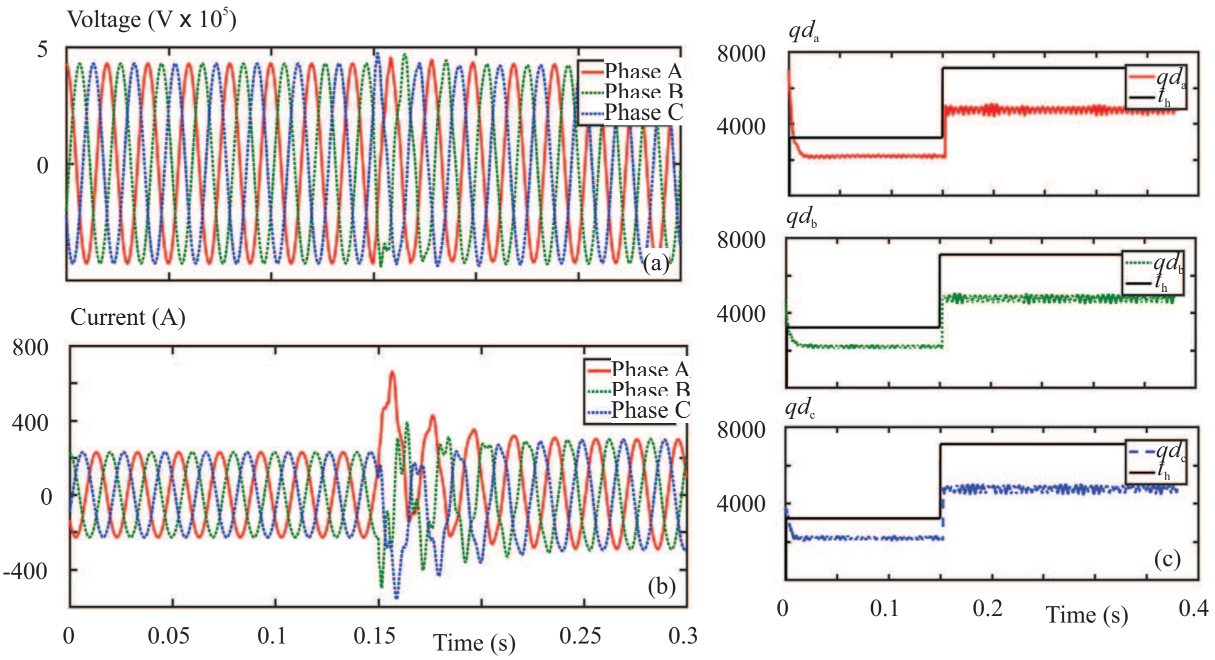

Fig. 5. The impact of load variation without faults: (a) – currents, (b) – voltages, and (c) – the behavior of SVDCs during load change

are measured as

$$\text{dependability} = \frac{\text{correct decisions}}{\text{desired decisions}} \times 100,$$

$$\text{security} = \frac{\text{correct decisions}}{\text{total decisions}} \times 100.$$

Considering all studied cases based on fault parameter variations, a total 1200 cases were simulated. The total number of corrective decisions was 1158 fault cases; therefore, the measured dependability of the proposed AFIS is 96.5%. Meanwhile, the term of security is key feature in a protective relay in which it measures the certainty grade that the relay will not run incorrectly. Furthermore, the security term is mainly dependent on the relay selectivity. To clarify the performance of proposed AFIS based on the security term, the security formula is expressed by (18). As mentioned above the total number of corrective decisions was 1158, but the aggregated fault decisions that the proposed AFIS reported including false decisions was 1188. Therefore, the percentage of security for proposed AFIS is 97.4747%. The AFIS has been investigated to compensated two-terminal transmission line with different compensating levels. Numerous healthy and unhealthy disturbances have been examined to prove the efficacy of the AFIS for different fault parameters. The results showed the ability of AFIS to identify short circuit fault and discriminate healthy disturbance (e.g., heavy load switching, source impedance variations, and loading change) correctly as in Fig. 5.

7 Flexibility of proposed method against heavy load switching

Most previous protection schemes under normal load condition can extremely operate well. In practice, the case of energizing heavy load may be occurred in electrical power grid, which leads to generate the transient prior to fault behaviour. Therefore, it is important to discriminate between heavy load and fault condition. Due to the fact that the energizing of heavy load is similar to a symmetrical three phase fault in electrical grid, a great number of protective relays provide false trips. Thus, the ability of proposed AFIS scheme to discriminate between faults and heavy loads is a critical issue. Consequently, the FDI is proposed to discriminate between the impacts of fault and heavy load condition. Six different cases are investigated in studied system at G2 as shown in Fig. 4 to evaluate the proposed protection scheme performance. Table 3 illustrates these cases that are relevant to energizing pure resistive (case-1), pure-capacitive (case-2), pure-inductive load (case-3) as 390 MW, 100, 150 MVAR, respectively. Also, 170-j156 MVA and 340-j310 MVA inductive loads (case-4 and case5), respectively, are considered with 195+j100 MVA capacitive load (case-6) to assess the proposed scheme. As observed in Tab. 3, the obtained results of proposed scheme involving FDI for heavy load connections exceed the fixed threshold, so the protection scheme avoids false tripping

Table 3. Simulation studies for energizing heavy loads at G2 in first system with $i_0 = 0$

Loading	qd_{a}	qd_{b}	qd_{c}	FDI	Fault decision
Normal load					
→	2.018×10^{3}	2.146×10^{3}	2.184×10^{3}	0.07	Healthy
Case-1	2.734×10^{5}	8.126×10^{5}	7.425×10^{5}	0.72	No fault
Case-2	1.012×10^{6}	1.460×10^{6}	1.624×10^{6}	0.35	No fault
Case-3	4.238×10^{5}	9.644×10^{5}	8.917×10^{5}	0.60	No fault
Case-4	2.492×10^{5}	4.712×10^{5}	3.631×10^{5}	0.61	No fault
Case-5	2.707×10^{5}	7.256×10^{5}	6.399×10^{5}	0.71	No fault
Case-6	2.452×10^{5}	6.819×10^{5}	6.088×10^{5}	0.72	No fault

Table 4. An assessment comparison between the suggested scheme with closed similar schemes in the literature

Reference	Signal type	Feature recognition tool	Sampling rate (kHz)	Data window (of cycle)	Network type	Max fault resistance (Ω)	Heavy load impact	Source impedance impact
[4]	I	DWT,db6 1-level	5 to 10	1/2	400 kV/4-bus, meshed system	1000	-	✓, ± 10% of base value
[5]	V	DWT, db4 4-level	5	1/5	400 kV/2-terminal system	100	-	✓, twice the base value
[6]	I	DWT, bior2.2 1-level	6.4	1/16	500 kV/2-terminal system	300	-	✓, +40% of base value
[7]	I	DWT, db1 1-level	6.4	1	500 kV/2-terminal system	50	-	-
[8]	I	DWT, Haar 1-level	6.4	1	500 kV/multi-terminal system	100	-	-
[9]	V&I	DWT, SVD 4-level	15.36	1/4	WSCC/nine-bus system	40	-	-
[11]	Reactive power	DWT, db1 1-level	6.4	1/8-	500 kV/Teed circuit	600	-	✓, ± 15% of base value
[14]	I	MWPT, RBFNN 1-level	10	1	500 kV/2-terminal systemt	300	-	-
[16]	I	ITD, SVD, PNN	1.2	1/2	500 kV/3-source systemt	130	-	-
[25]	V&I	WT norm entropy	8	1-	400 kV/compensated 2-terminal system	-	-	-
Proposed in this work								
	Reactive power	DWT, db6 1-level	6.4	1/16	500 kV compensated grid	-	✓	✓

8 Assessment study of fault identification scheme

An assessment study has been addressed to evaluate and compare the suggested scheme with other similar schemes in the survey. The data is classified according to required signal type, feature recognition tools, sampling rate used, network configuration type, maximum fault resistance, heavy load impact, source impedance variation as well. The performance of the proposed scheme is assessed with existing fault identification schemes which applied to the compensated network configurations as can be seen in Tab. 4.

The main gap in the existing schemes is that they have not dealt with the impact of heavy load switching while the proposed scheme is validated to this issue. The proposed scheme has capability to discriminate between the fault and heavy load condition without any false tripping in the almost test cases. Further, the proposed study is only based on the reactive power measurements corresponding to three phases during disturbance whether healthy disturbance or unhealthy disturbance. Using reactive power measurements as input signals can cope with high fault resistance, this issue uncovered in [5, 7, 9, and 25]. This is right because it works with reactive power measurements (Q) during faults, which is based on the production of current and voltage signals for their computation. It is well-known that the greater fault current is accompanied by the less voltage and vice versa. Despite methods based PNN and RBFNN as in [15, 17] are quite successful in fault identification task, the main gab of these studies is that they require a huge amount of training effort for high performance. On the other hand, the proposed scheme does not require any artificial classifier technique, it based on only the logic flow concept. It is observed that the proposed scheme has fast response as shown in Tab. 4 it needs only 1/16 of cycle data window to make final decision.

9 Conclusions

In this study, the adaptive fault-identification relay was proposed to discriminate between heavy load switching and fault occurrence on transmission lines. Based on the influence of reactive-power behaviour during faults, the proposed scheme could detect and classify short circuit faults for compensated transmission network correctly. The details wavelet coefficients with one-level of decomposition were employed to recognition the empirical fault scenarios on transmission network. The proposed technique was dependent on the adaptive threshold value that was estimated according to the correlative concept among the sum of details coefficient based on reactive power computations corresponding to three phases. The key factors that inuence the analysis of the transients produced as the fault occurrence were considered. Moreover, the reliability of the proposed scheme with healthy disturbance was also tested by varying load changing, source impedances. In addition, the response of proposed scheme based on dependability and security were discussed and the obtained results showed that the proposed AFIS has a good performance. The effects of series compensated transmission line were evaluated under different compensation levels. It was observed from simulation results that the proposed method was able to detect and classify faults at different fault scenarios. The analysis results indicated that the proposed approach achieves satisfactory performance with a low misdetection rate and an acceptable reaction speed to fault.

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