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مخطط حاكمة الحماية المسافية الرقمية لنظام النقل ذات الجهد العالي بدمج مفهوم مؤشر القوة المنظمة (RPI) باستخدام قياس تزامني

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** مختبر الجهد العالي في 1200 / 765 / 400 / 220 كيلو فولت، محطة واردها الفرعية، شركة شبكة الكهرباء الهندية المحدودة.

الخلاصة

في هذا البحث العمل، جديدة كل مرحلة نظام الحماية من دون تعويض وكلاهما إنهاء السلسلة خط نقل تعويض يقترح استخدام قياس متزامنة لوائح السلطة الفهرس (RPI). يتم تعريف RPI كل مرحلة كالنسبة مجموع الطاقة الظاهر نهاية الإرسال والاستلام نهاية السلطة الظاهر إلى السلطة في نهاية المتلقي لتلك المرحلة. تم تطوير هذا النظام للكشف عن خطأ، وتحديد المرحلة الخاطئ والتعثر في مرحلة خلل كتعويض نظام ترحيل الذي الأولوية العليا في حماية سلسلة خطوط. هذا المخطط لديه حصانة لتعويض السلسلة الحالية وخط شحن نهاية الحالية والأخرى في تغذية التأثير الحالي والكشف عن الأعطال داخل دائرة نصف. المخطط المقترح يستخدم دورة واحدة فقط تحريك الإطار، نموذج بعينه فحص المعلومات وانخفاض عبء الحسابية، قرار سريع بمعدل عال من الدقة حتى في وجود مقاومات خطأ عالية. المحاكاة هي جداول النتائج لوفرة حالات الاختبار النظر في الظروف الشديدة خطأ مع المقاومة منخفضة جداً، تحميل التعدي خطأ عالية مقاومة الظروف، أخطاء داخلية وخارجية مع المكثفات سلسلة ثابتة (FSC) في مواقع مختلفة. الجدة من هذه الخطة هو أنه لا يوجد أي شرط لتغيير إعدادات العتبة المقترحة التتابع حتى مع مختلف مواقع التثبيت في منتدى التعاون الأمني، ومستويات التعويض %، عملية وضع تجاوز منتدى التعاون الأمني الذي يجب أن يتغير في إعدادات ترحيل الرقمية التقليدية والحديثة. تثبيت البيانات MATLAB / SIMULINK نموذج التي تم إنشاؤها باستخدام الفعلي 400 كيلوفولت 400- كم حقيقي نظام نقل المعلمات قد استخدمت للتحقيق في مستوى دقة المخطط. نتائج الأداء أظهرت هنا تفوق RPI على أساس نظام التحقق من صحة عبر أنظمة الحماية التقليدية. تجارب المحاكاة واسعة النطاق تسليم النتائج الدقيقة التي تبين درجة عالية من الدقة والبساطة ومتانة النظام المقترح.

Digital relaying scheme for EHV transmission system incorporating regulated power index (RPI) concept using synchronized measurement

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ABSTRACT

In this research work, a new per phase protection scheme of uncompensated and series compensated transmission line is proposed using both end synchronized measurement Regulated Power Index (RPI). RPI per phase is defined as the ratio of the sum of sending end apparent power and receiving end apparent power to the power at receiving end for that phase. This scheme is developed for the detection of fault, identification of faulty phase and tripping the faulty phase as a relaying scheme which is of supreme priority in protection of series compensated lines. This scheme has immunity to series compensation current, line charging current and other end in-feed current effect and detects the faults within half cycle. Proposed scheme uses only one cycle moving window, sample by sample checking information and has low computational burden, fast decision with high rate of accuracy even in presence of high fault resistances. The simulation results are tabulated for abundant test cases considering severe fault conditions with very low resistance, load encroaching high fault resistance conditions, internal and external faults with Fixed Series Capacitors (FSC) at various prime locations. Novelty of this scheme is that there is no requirement to change the proposed relay threshold settings even with different FSC installation locations, % compensation levels, FSC bypass mode operation which has to be changed in conventional and modern digital relay settings. MATLAB/SIMULINK model generated data using an actual installed 400 kV- 400 km real transmission system parameters have been used to investigate the accuracy level of the scheme. The performance results demonstrated here validate the superiority of RPI based scheme over conventional protection schemes. Extensive simulation experiments deliver accurate results, which demonstrate high accuracy, simplicity and robustness of the proposed scheme.

Keywords: Fault detection; power system faults; power system protection; transmission lines.

INTRODUCTION

Thetransmission grid system demands more power transfer capability and increased voltage level for loss cutback without risking stability of the system. Considering the right of way (ROW) and other environmental impacts, it has become a tough task to construct new transmission lines (Rahmani et al., 2013). Increasing the power transfer capability without compromising system stability of existing transmission networks is achieved with various series compensation techniques. Fixed series capacitors (FSC) have been proven as one of the beneficial and cost effective measures over the years. But, presence of FSC in transmission system leads to a conventional impedance based distance relay to mal-operate numerous times, causing disruption in power and interruption in grid stability. This happens due to non linear high capacitive currents produced by series capacitors during abnormal conditions. Moreover, non linearity produced with overvoltage protection of FSC by metal oxide varistor (MOV) and spark gap in parallel to capacitors adds up in improper calculation of impedance based distance relying schemes during faults. As a result, protection relay of transmission line over-reaches or under-reaches in an unpredictable manner (Ahmed et al., 2012; Vyas et al., 2014). So, changes in relay settings are to be made to eliminate adverse effects of series compensation, which is not a practicable job always. At present, quadrilateral characteristics are used for distance protection of 400 kV fixed series compensated transmission line and are reported to perform less accurately in estimating fault location distance.

A bibliographical analysis of effects of series compensation on protection of transmission line and new methods to overcome these ill effects are presented in Vyas et al. (2014). Reference Dambhare et al. (2009) gives a new scheme of current differential protection applying steady-state phasor estimation for normal transmission line and extension to series compensated line. In Darwish et al. (2005), a latest line protection method based on the difference and averages of per phase active and reactive power in the line are compared for fault detection. An interesting uncompensated line protection concept of fault component integrated power, which is the difference between pre-fault and post-fault integrated powers, is introduced in Bolandi et al. (2014). But threshold value has to be changed for series compensated line in Bolandi et al. (2014), which is not the issue in proposed scheme. The article by Abdelaziz et al. (2013) gives a fault-location algorithm generalized model for both normal and transmission lines with series compensation. Algorithm in Abdelaziz et al. (2013) requires the synchronized measurements of currents and voltages at both ends of the line and adjusts series-compensation element voltage drop in the estimation formula, but results for high fault resistance are not depicted. References He et al. (2011), Suonan et al. (2011a), Suonan et al. (2011b), He et al. (2013a) and He et al. (2013b) introduces a pilot protection method using fault component integrated impedance measurement, which is defined as the ratio of the sum of the fault component voltage phasors of the two endsof the transmission line to the sum of the current phasors of fault component of the that line. This integrated impedance concept is used to check, whether there is a fault inside the line or outside the line. The same integrated impedance formula based protection methodology in SVC compensated line is used in Gupta & Tripathy (2014). Reference Yu et al. (2002) gives a fault location estimation algorithm in series compensated line using PMUs at both ends with the assumptionthat fault resistance is purely resistive and fault type is already known. Imaginary part of integrated impedance measurement is used in fault classification of UPFC and TCSC compensated lines by Jena & Samantaray (2014a) and Jena & Smantaray (2014b) respectively, but changes to be made in the scheme (in case of uncompensated line) are not specified. Using post fault one cycle differential features of sequence components of two ends voltages and currents, a differential relaying scheme for lines with UPFC in wind farms is developed in Jena & Smantaray (2016). One more relaying scheme is given for uncompensated double circuit lines in Jena & Smantaray (2015), which uses phase angle of differential impedance signal to check whether the fault is in internal section or external.

The protection problems in transmission systems with FSC can be solved by the developing dedicated relaying schemes. In series compensated transmission line, detection and identification of correct faulty phase is a major issue with schemes available in literature. Looking at the mentioned protection issues faced by the existing protection schemes due to series compensation, there is a strong need to develop a novel all-inclusive relaying scheme for series compensated transmission lines. Considering the motivation of the utmost priority to accurately detect and trip the faulty phase and protect the costly capacitor banks in series compensated transmission line, authors have focused and developed this regulated power index (RPI) based relaying scheme particularly for fault phase detection and identification with simultaneous fast tripping decision to fault phase in order to isolate the faulty section in the system.This paper introduces a new concept called RPI based new per phase protection scheme for uncompensated as well as fixed series compensated transmission lines. Such a novel concept has never been used in recent decades in relaying schemes. RPI is defined as ratio of summation of power of sending and receiving end to the receiving end power. The power used in RPI is calculated as product of voltage and current phasors at a particular instance. Then the real part of RPI is used in tripping decision. Motivation behind using the regulated power is that the power regulation profile in a transmission system is constant. When there is any critical disturbance or fault in the line, this power profile will change suddenly. As a result, change in this power regulation can be used as a deciding variable for fault detection. In order to overcome reactive power loss variations due to line length, real part of RPI has been considered. This new concept of RPI based relaying scheme can be used as a main relay. In this research work, the 400 kV transmission line of Western Grid of Powergrid Corporation of India Ltd. is simulated to validate the proposed scheme. It comprises of an equivalent model of 400 kV single circuit transmission line of 400 km length with two end buses and FSC with protection scheme based on the real system parameters of the actual installed system. Distributed parameter transmission model is applied in system modeling. Figure 1 shows the considered equivalent single-line plan of actually installed 400 kV FSC as mentioned above.

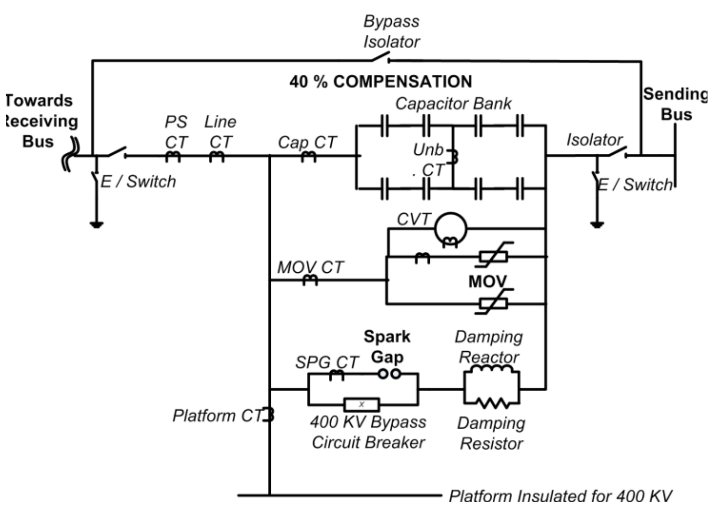

Fig. 1. Single-line plan of actual installation of 400 kV FSC

This research paper presents a unique and simple method for protection of a double end fed transmission system. All the ten types of internal and external shunt faults using two terminal data, i.e. sending and receiving end voltage and current phasors are considered. The effects of varying internal and external fault types, FSC installation locations, fault distances, degree of compensation, fault resistances, fault inceptions and sudden power loading changes have been studied in order to validate this scheme thoroughly. The performance of the proposed scheme has been investigated by a number of offline tests for internal as well as external faults. The simulation test results show that this RPI based new protection scheme works satisfactorily during faults providing instant protection to the line. Moreover, performance analysis shows that the proposed scheme also works properly in uncompensated line. Such extensive work has not been reported earlier for fault detection and protection relaying methods of fixed series compensated line. Authors have tried to build an entirely new and simple concept, which has proven to be fast and less complex.

FORMULATION OF RPI

In this research work, one cycle Discrete Fourier Transform (DFT) is used to get voltage and current phasor samples from sending as well as receiving end. Any signal X(k) with DFT can be written as Equation(1) for kth sample, where A0 , An and ɵn are the DC component, the magnitude and the phase angle of the nthorder harmonic component, respectively. The input signal X(k) is then passed through an anti aliasing filter where N is number of samples per cycle.

$$X(k) = A_0 + \sum_{n=1}^{N} A_n \cos\left(\frac{2\pi nk}{N} + \theta_n\right) \tag{1}$$

$$X_r = \frac{2}{N}\sum_{k=1}^{N} X(k)\cos\left(\frac{2\pi k}{N}\right) \tag{2}$$

$$X_i = \frac{2}{N}\sum_{k=1}^{N} X(k)\sin\left(\frac{2\pi k}{N}\right) \tag{3}$$

$$X_m = \sqrt{X_r^2 + X_i^2} \tag{4}$$

$$\theta = \tan^{-1}\left(\frac{X_i}{X_r}\right) \tag{5}$$

Xr, Xi,Xm and q are the real part, imaginary part, magnitude and phase angle of the fundamental phasor of X(k),respectively. Hence, fundamental phasorX1 can be written as Equation (6).

$$X_1 = X_m \angle \theta \tag{6}$$

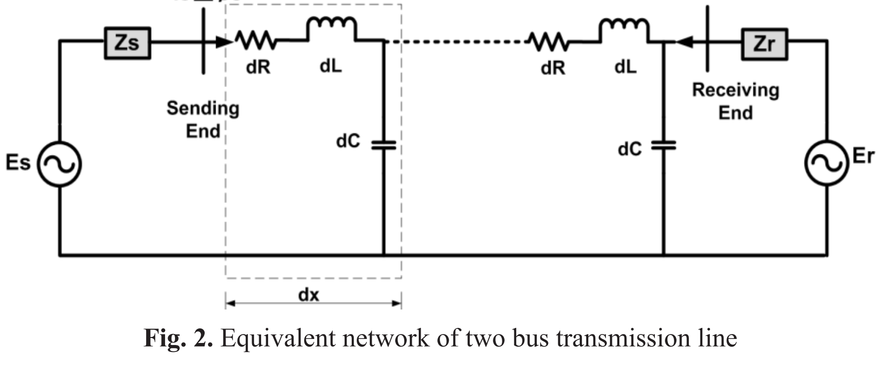

Fig. 2. Equivalent network of two bus transmission line

Figure 2 shows the equivalent model of two bus transmission line network with dR, dLand dC as distributed resistance, inductance and capacitance respectively for incremental line length dx. ZsandZr are the source impedances of sources Esand Er respectively.

Sending end and receiving end per phase apparent power are calculated from Figure 2 as,

$$S_{Si} = V_{Si}\angle\theta_{Si} \times I^{*}{}_{Si}\angle\phi_{Si} \tag{7}$$

$$S_{Ri} = V_{Ri}\angle\theta_{Ri} \times I^{*}{}_{Ri}\angle\phi_{Ri} \tag{8}$$

Where, SSi and SRiare are the sending end and receiving end apparent powers for ithphase, respectively. RPI for ith phase is defined as the ratio of the sum of sending end apparent power and receiving end apparent power to the power at the receiving end for that phase. Calculation of RPI is done per sample basis for each phase continuously. RPI for ith phase is given by Equation (9) as,

$$RPI_i = \left(\frac{S_{Si} + S_{Ri}}{S_{Ri}}\right) \tag{9}$$

Substituting values of Equations (7) and (8) in Equation (9) we get,

$$RPI_i = \left[1 + \left(\frac{V_{Si}\angle\theta_{Si}}{V_{Ri}\angle\theta_{Ri}}\right)\left(\frac{I^{*}{}_{Si}\angle\phi_{Si}}{I^{*}{}_{Ri}\angle\phi_{Ri}}\right)\right] \tag{10}$$

The power regulation profile in a given transmission system remains unchanged for given loading conditions. Ideally, if we consider sending end power and receiving end power to be equal then the RPI ratio is 2. When there is any fault in the line, both ends power profile will change suddenly followed by change in RPI ratio from 2 as during fault, sending end and receiving end powers are not same. This change in RPI ratio can be used to detect the fault in faulty phase as in healthy phase RPI ratio does not change in comparison with faulty phase.Variations in sending and receiving end voltages and currents are taken into consideration in Equation(10). The angle in between the two equivalent sources of the sending and receiving ends of the transmission system is less than 30° under normal working condition. In this research work, real part of RPI is calculated to decide the trip decision per phase. This real part of RPI is given as (RRPI),

$$RRPI_i = \mathrm{Re}\left(\frac{S_{Si} + S_{Ri}}{S_{Ri}}\right) \tag{11}$$

Change in RRPI is a measure of change in signature due to fault in the transmission system. So, change in RRPI per sample for ith phase is given by delRRPIias,

$$\mathrm{delRRPI_i} = \left|\mathrm{RRPI_i(k) - RRPI_i(k-1)}\right| \tag{12}$$

In this way, the proposed new concept of RPI based relaying can be easily applied in transmission system. In support with this theoretical analysis, the proposed RPI based fault detection and per phase trip protection has been validated with simulation results in results and performance evaluation sectionsat the end of paper respectively.

SYSTEM PARAMETERS AND MODELING

Implementation and consistency of the proposed scheme are investigated with the help of fault analysis data of 400 kV power system simulated in MATLAB/SIMULINK software. Actual 400 km, 400 kV series compensated transmission system parameters are considered for modeling. A two bus three phase50 Hz,400 kV transmission system as depicted in Figure 3, has been used in simulation, to test and validate the proposed scheme. The power system comprises two sources with buses, 400 km transmission line, FSC with its associated protecting components, GPS synchronized measurement units and proposed relay with fiber optic links for measurement of data retrieving to relay. The transmission line is simulated using a distributed parameter line model. The FSC installation location is varied at sending end, midpoint and receiving end of the transmission line. The transmission line parameters and other real time data at bus used for simulation purpose are specified in the Appendix .

Total line reactance is Xl = 107.6 Ω. The capacitive reactance of FSC is Xc = 43.04 Ω which is 40% of the total line reactance and Xc = 26.9 Ω for 25% compensation. Maximum current rating of capacitor bank is designed for 3000 A. The maximum continuous operating voltage of MOV is designed at 130 kV. MOV being a non-linear resistive element, it has limit on energy dissipation and hence an overload protection is provided to protect it against excessive heat. The overload protection measures the energy engaged by the MOV and a parallel spark-gap is triggered, if the energy crosses a threshold limit i.e. 15 MJ used for this study.

In practice, these measurements are done with 0.2 accuracy class current transformers (CT) and capacitive voltage transformers (CVT), which give highly accurate measurements and saturation effects of measuring current and voltage transformers can be avoided. Also, the measurements on both the ends are GPS synchronized with accuracy of 1 μs, which corresponds to 0.018° of small error in 50Hz system so that samples of same time stamps are compared.Assuming time stamped GPS synchronized measurement at both the terminals with high speed optical fiber data communication system, which transfers information at relaying bus without any communication delay as shown inFigure 3.Sampling rate affects the relay operation time. In practice, sampling frequencies ranging from 1 kHz to 2.5 kHz are used. It has been observed that, higher sampling rate gives fastest relay operation. However, only marginal gains in speed of relay operation reduce the accuracy at higher sampling frequencies i.e., a result in accord with the law of diminishing marginal utility. Also, higher sampling rate requires more samples to be checked for the set-threshold criterion to maintain reliability of the operation, which in turn will increase the computational burden. Keeping the existing actually implemented practice in mind, authors have used 1 kHz sampling rate for reliable and fast operation as used in most of the referred papers in the manuscript.

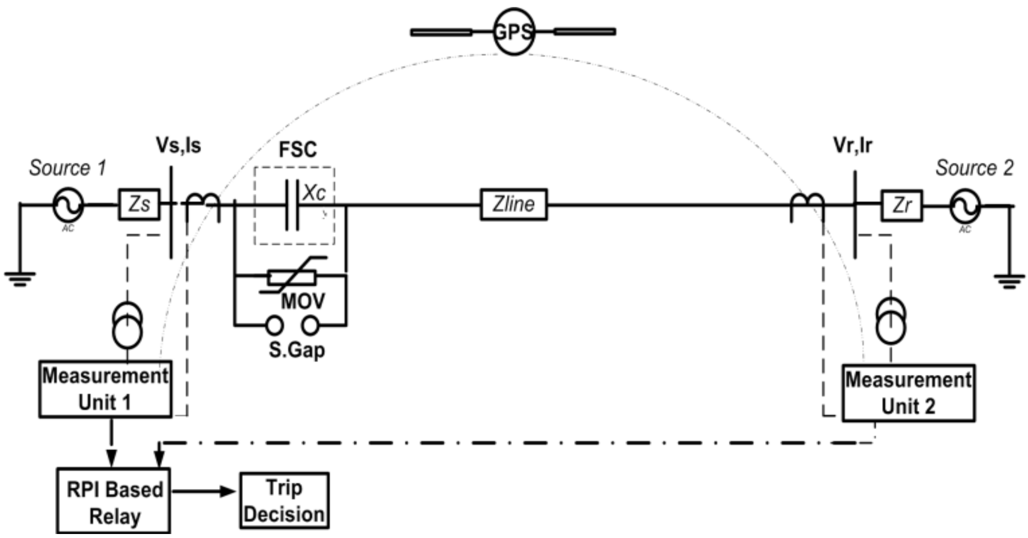

Fig. 3. Single line diagram of proposed relaying scheme

PROPOSED PROTECTION ALGORITHM

The use of RPI concept in line protection makes the proposed scheme very simple and adaptive for all types of faults. Discrete sampling frequency of 1 kHz is used, i.e. 20 samples/cycle in simulation. Sample by sample checking offers more accuracy in this scheme. The main structure of the proposed algorithm is depicted in Figure 4. The algorithm explanation is as follows.

1. In the first step, per phase voltage and current at sending bus continuously measured by metering instruments are sent to proposed relay. Also per phase voltage and current at receiving bus from remote end are transferred to relay through high speed dedicated communication link having fiber optic connectivity. These signals are GPS time stamped and considered as input data of the algorithm with no communication delay.
2. In the second step, these input signals are passed through anti-aliasing filter and then one cycle moving window DFT is applied to these input signals to extract current and voltage phasors of both ends.
3. In the third step, per phase RRPI is calculated as explained in formulation of RPI section and simultaneously per phase delRRPI is also calculated.
4. In the final step, per phase delRRPI criterion is simultaneously checked.If delRRPI >set-threshold in five samples, then send trip signal to that particular phase circuit breaker (CB). Else return tostep 2. As soon as this sample value crosses the threshold counter five times, phase trip signal is extended to CB. The calculated set-threshold value is given in simulation results section.

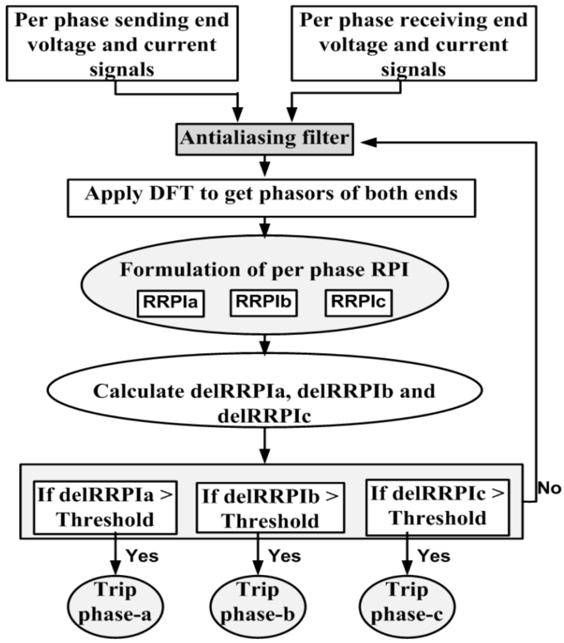

Fig. 4. Outline of proposed algorithm

SIMULATION RESULTS

To validate the proposed relaying scheme, the model with the actual installed real system parameters was designed in Matlab/Simulink software. The scheme was tested on more than 20000 fault cases as mentioned in Table 1.

Table 1. Test data creation for fault cases

Variation	Range
FSC position	Bypass mode, sending end, midpoint and receiving end
Type of fault	a-g, b-g, c-g, a-b, b-c, a-c, a-b-g, b-c-g, a-c-g and 3-ph
%Compensation	25% and 40%
Fault location	5 km to 395 km (in step of 5 km from relaying end)
Fault resistance (Rf)	0.01 Ω - 400 Ω
Fault inception	0.1 s to 1 s (in step of 0.1 s)

The threshold value used in the proposed scheme was obtained by performing rigorous simulations considering severe fault cases like realistic fault resistance, fault location very near to FSC as well as far away from FSC with sudden power loading changes at bus during various fault instances.Ideally sending end power is equal to receiving end power, so let us assume SSi and SRi as 1 pu each. Hence, the RPI ratio from Equation(9) is calculated as 2. Let us now consider a sudden loading change of 0.2 pu, which will make SSi and SRi as 1.2 pu each. So, the new RPI ratio in this loading change is still calculated as 2. Therefore, in normal condition or even atsudden load change condition, the RPI ratio remains constant. But, in case of fault condition, SSi and SRi powers are not same and varies depending upon fault location and other parameters, which in turn will change the RPI ratio i.e. it will not be 2. RPI ratio will have deflection from the normal value. This change or deflection in the RPI ratio was used as a signature to detect the fault per phase, denoted as delRRPI. The transmission line compensated with FSC is operated near to thermal limit of loading and even small change in fault current can damage the capacitor banks, which is not at all recommended considering the importance of the line and critical load flow. Also, rate of change of fault current is low in high Rf faults. In order to make the proposed scheme highly sensitive even in case of high resistance faults, the threshold was set to a low value 0.005.To make the scheme more reliable, trip decision was set to be issued only when 5 samples crossed the threshold value. Further validation was achieved by considering 4 cases for internal faults as FSC bypass mode i.e. normal uncompensated line, FSC at sending end, FSC at midpoint and FSC at receiving end respectively. Also, external fault cases were considered and validated. Each case is explained with graphical result obtained as follows.

Uncompensated or FSC bypass mode

In this case, FSC was kept in bypass mode i.e. normal uncompensated transmission line mode. Outputs of delRRPI vs time at randomly chosen fault distances, types, Rf and fault instances were checked so as to get further reliability and more accuracy in this protection scheme. Figure 5 gives an overview of test results in this bypass mode for an internal a-b-g fault at 380 km distance from sending end with Rf = 200 Ω. Fault was created with fault inception at 0.35 sec. As per the proposed criterion, if delRRPI value is more than 0.005 threshold in 5 samples, then fault is detected and trip signal is passed for that respective phase. As per this criterion, fault was detected at 0.355 sec in a-phase and at 0.358 sec in b-phase respectively as in Figure 5. So, fault detection times were 5 ms and 8 ms in phases a and b respectively after fault inception. Whereas, there was no fault detection in c-phase as RRPI value did not cross the set-threshold value.

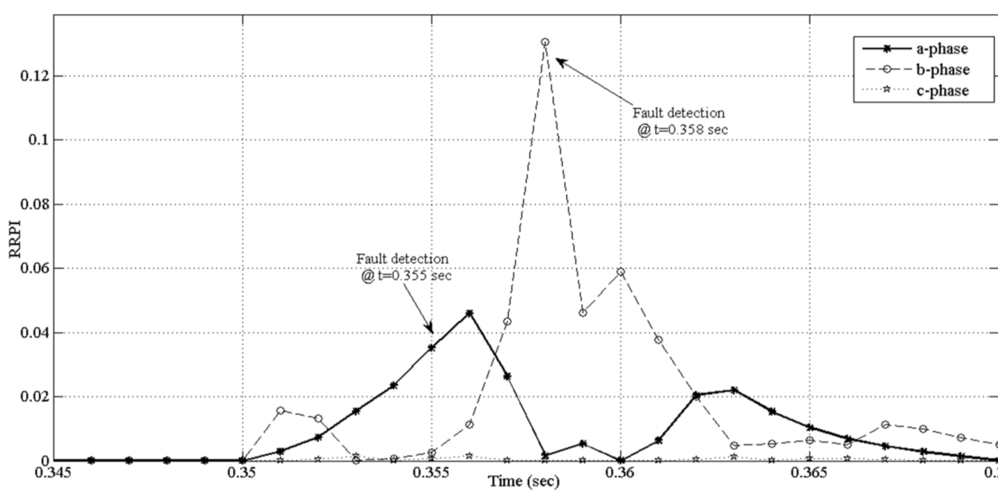

Fig. 5. Simulation plots of per phase delRRPI for a-b-g fault at 380 km distance with Rf = 200 Ω and with fault inception at 0.35 sec

FSC at sending end

In this case, FSC was placed at sending end of the transmission line. Figure 6 gives an overview of test results in this mode of FSC at sending end with 40% compensation for b-g fault at 25 km distance from sending end with $R_f = 0.1\ \Omega$. Fault was created at 0.25 sec. As per the fault detection set criterion, fault was detected at 0.258 sec in b-phase as in Figure 6. So, fault detection time was found 8 ms in a-phase after fault inception. Whereas, there was no fault detection in phases a and c as RRPI value did not cross the set-threshold value.

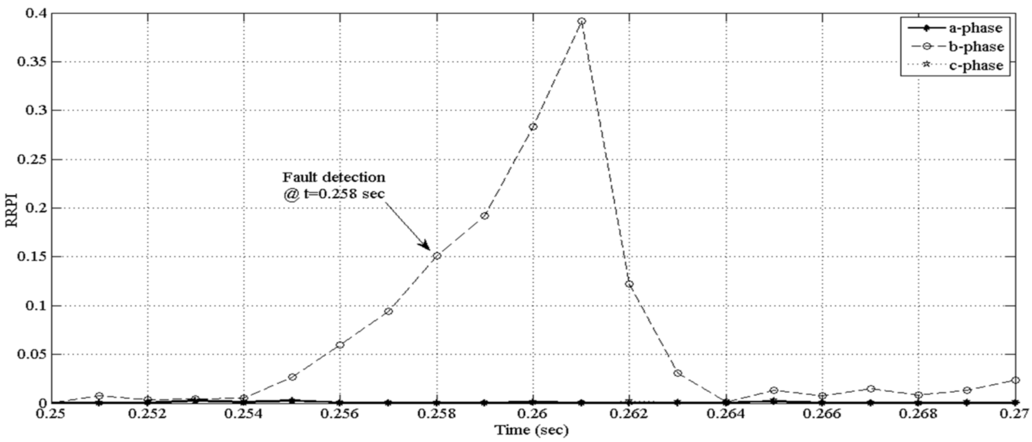

Fig. 6. Simulation plots of per phase delRRPI with 40% compensation for b-g fault at 25 km distance with $R_f = 0.1\ \Omega$ and with fault inception at 0.25 sec

FSC at mid point of line

In this case, FSC was placed at mid point of the transmission line. Figure 7 shows test result in this mode of FSC at mid point with 25% compensation for c-g fault at 30 km distance from sending end with $R_f = 0.1\ \Omega$ and with fault inception at 0.37 sec.

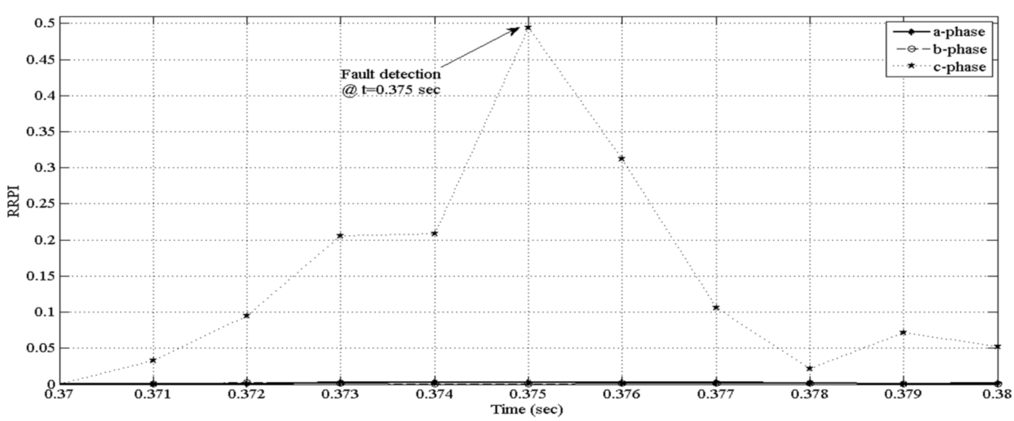

Fig. 7. Simulation plots of per phase delRRPI with 25% compensation for c-g fault at 30 km distance with $R_f = 0.1\ \Omega$ and with fault inception at 0.37 sec

As per the fault detection set criterion, fault was detected at 0.375 sec only in c-phase in Figure 7. So, fault detection time was found 5 ms in c-phase after fault inceptionas in Figure 7. Whereas, no fault was detected in phases a and b as RRPI value did not cross the set-threshold value.

FSC at receiving rnd of line

In this case, FSC was placed at receiving endof the transmission line. Figure 8 shows test result in this mode of FSC at remote end with 40% compensation for a-b-g fault at 295 km distance from sending end with $R_f = 1\ \Omega$ and with fault inception at 0.5 sec. As per this criterion, fault was detected at 0.507 sec in a-phase and at 0.506 sec in b-phase respectively as in Figure 8. So, fault detection times were 7 ms and 6 ms in phases a and b respectively after fault inception. Whereas, there was no fault detection in c-phase as RRPI value did not cross the set-threshold value.

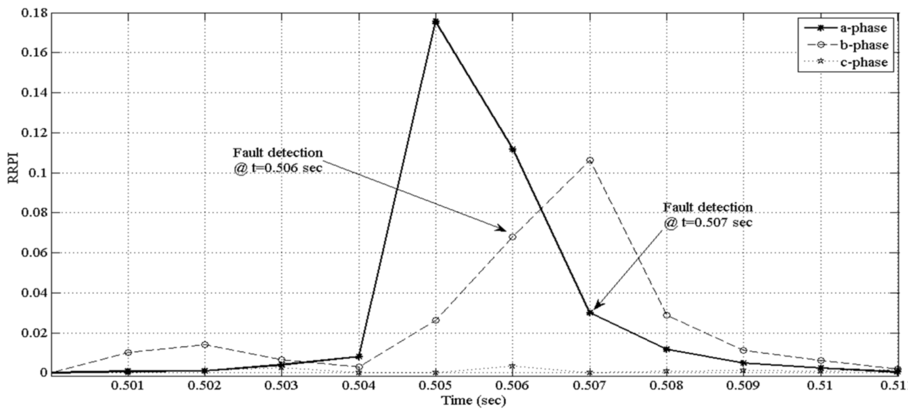

Fig. 8. Simulation plots of per phase delRRPI with 40% compensation for a-b-g fault at 295 km distance with $R_f = 1\ \Omega$ and with fault inception at 0.5 sec

For the same fault parameters as above, proposed scheme was tested for a-b fault and results aredepicted in Figure 9. So, fault detection times were 8 ms and 9 ms in phases a and brespectively after fault inception for a-b fault at 0.5 sec. Proposed scheme worked accurately when compared for a-b (L-L) and a-b-g (L-L-G) faults.

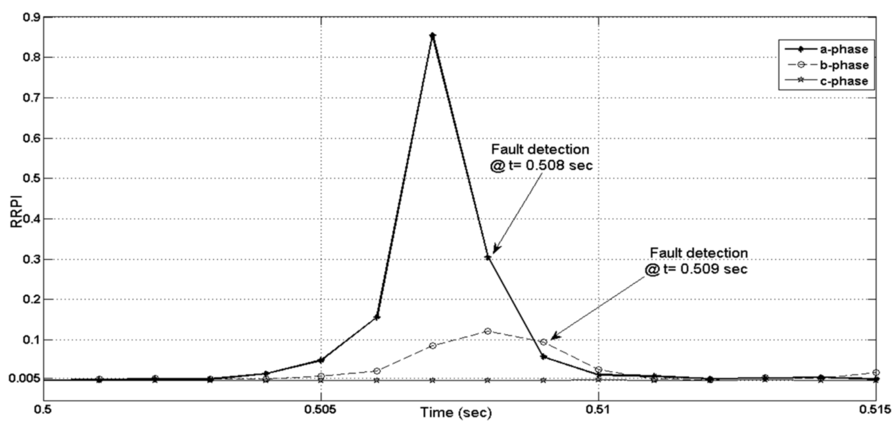

Fig. 9. Simulation plots of per phase delRRPI with for a-b fault with $R_f = 1\ \Omega$ and with fault inception at 0.5 sec

External fault cases

Numerous external fault cases were performed considering faults behind FSC, i.e. creating various faults in other line sections. For external faults, it was observed that the RRPI values did not cross the set threshold and the proposed relay restrained from operation. Figure 10 shows two of such randomly selected test cases for external faults, when FSC was placed at sending end. Figure 10(a) depicts external fault case of a-c-g fault at a distance of 30 km behind FSC in other line with $R_f = 0.1\ \Omega$ and with fault inception at 0.25 sec. Figure 10(b) depicts external fault case of 3-phase fault at a distance of 50 km behind FSC in other line with $R_f = 1\ \Omega$ and with fault inception at 0.33 sec. Even after varying the fault properties in external fault casesas in Figure 10, this relay did not operate for external fault. The proposed protection relay operated for few severe external fault cases only for fault distance below 5% of the total line length when FSC was placed near sending end.

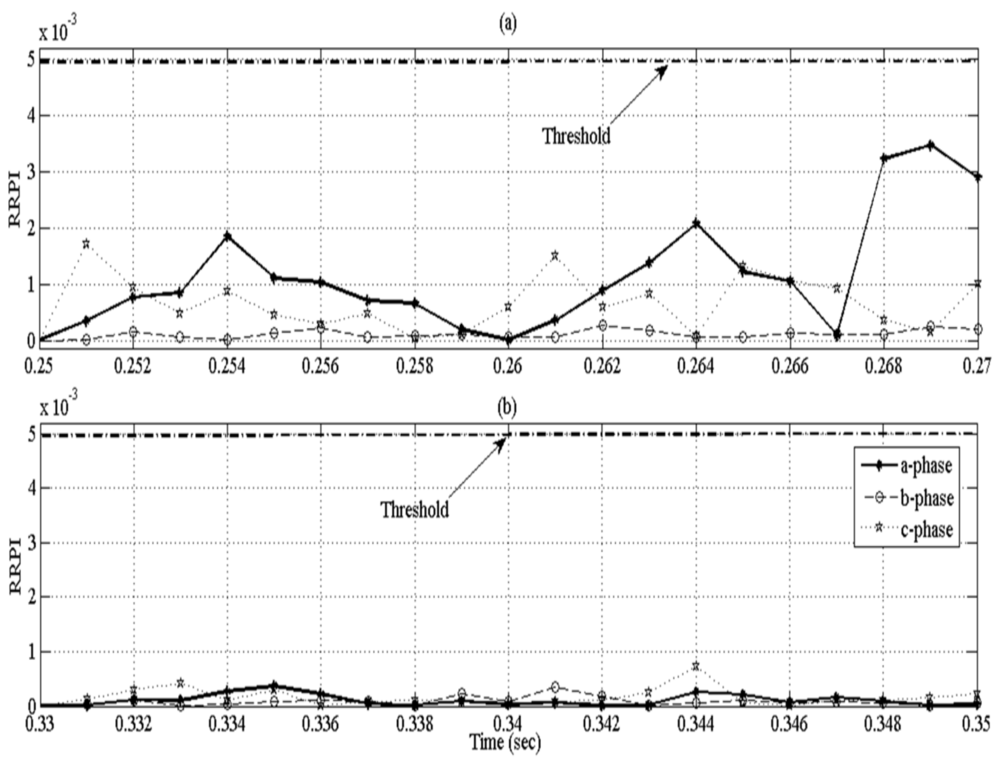

Fig.10. Simulation plots of per phase delRRPI for external fault cases of (a) a-c-g and (b) 3-phase faults

PERFORMANCE EVALUATION

In order to get more clarified vision on effect of fault parameters on proposed scheme, various internal and external faults, such as single phase to ground, double phase to ground, double line and three-phase faults at different locations measured from relay location on transmission line and at different fault inceptions with wide range of fault resistances were comprehensively investigated.

Overall consolidated results with above mentioned varying fault properties are tabulated in Table 2. Time of fault detetion in each faulty phase observed by simulations for particular fault are given in last three columns of Table 2.In Table 2, ND represents fault not detected in phase.

Table 2. Overall test results for various fault cases

FSC location	%Comp-en-sation level	Type of fault	Fault dist. (km)	$R_f (\Omega)$	Fault inception instance (sec)	Fault detection instance in faulty phases (sec)		
						Ph-a	Ph-b	Ph-c
Bypass	No .Comp	a-g	15	0.1	0.20	0.208	ND	ND
		a-b	180	1	0.24	0.247	0.246	ND
		a-b-c	270	10	0.31	0.315	0.315	0.318
		a-b-g	380	200	0.35	0.355	0.358	ND
Sending end	25%	b-g	25	0.1	0.25	ND	0.256	ND
		a-b-c	120	1	0.30	0.306	0.305	0.305
		b-c-g	210	10	0.35	ND	0.358	0.356
		b-c	345	100	0.40	ND	0.407	0.405
	40%	b-g	25	0.1	0.25	ND	0.258	ND
		a-b-c	120	1	0.30	0.306	0.308	0.305
		b-c-g	210	10	0.35	ND	0.355	0.358
		b-c	345	300	0.40	ND	0.406	0.407
Mid point	25%	c-g	30	0.1	0.37	ND	ND	0.375
		a-c	165	1	0.40	0.406	ND	0.405
		a-b-c	215	10	0.43	0.435	0.436	0.435
		a-c-g	375	100	0.47	0.475	ND	0.475
	40%	a-b-c	30	0.1	0.37	0.376	0.377	0.375
		a-c	165	1	0.40	0.407	ND	0.405
		a-g	215	10	0.43	0.437	ND	ND
		a-c-g	375	100	0.47	0.477	ND	0.475
Receiving end	25%	a-g	360	0.1	0.65	0.656	ND	ND
		a-b-g	295	1	0.50	0.507	0.506	ND
		a-b-c	170	10	0.55	0.557	0.555	0.556
		a-b	90	100	0.87	0.876	0.877	ND
	40%	a-g	360	0.1	0.65	0.657	ND	ND
		a-b-g	295	1	0.50	0.507	0.506	ND
		a-b-c	170	10	0.55	0.558	0.556	0.555
		a-b	90	100	0.90	0.908	0.905	ND

The trip decisions with the proposed scheme for the same fault conditions stated in Figure 8 are checked for the set criteria and are shown in Figure 11. From Figure it is clear that for a-b-g fault at 0.5 s, fault is detected only in a and b phases as per set threshold in 7 ms and 6 ms respectively and hence proves the accuracy of the scheme.

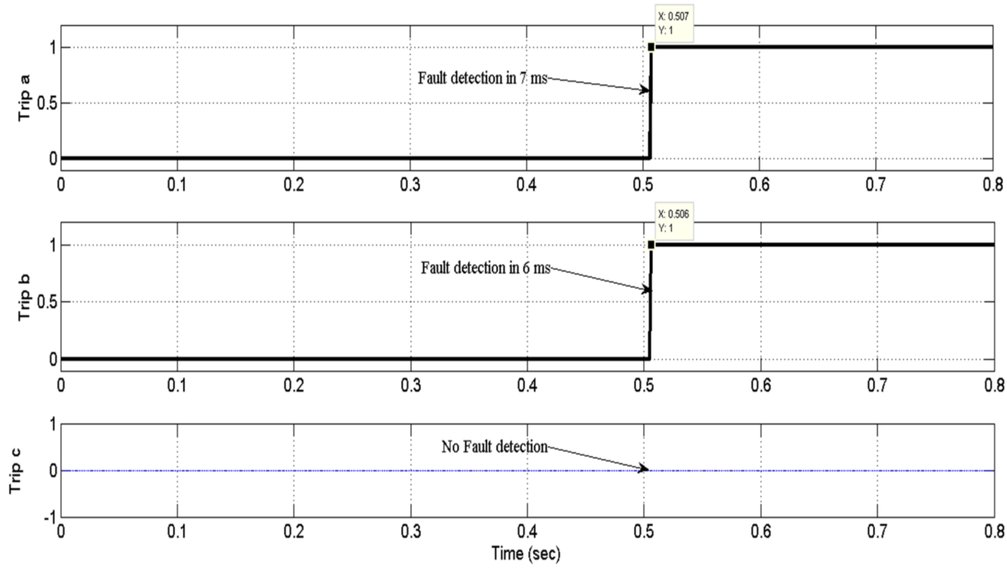

Fig.11. Trip decision plots per phase for a-b-g fault with inception at 0.5 sec

All these broad range of simulation results established the following superior inferences:

- The proposed RPI based protection scheme worked satisfactorily in uncompensated mode as well as series compensated mode independent of installation position of FSC and it did not mal-operate for external faults.
- The proposed protection scheme provided protection to complete section of EHV transmission line independent of location of FSC, while conventional distance protection schemes provide protection to 80%-85% of the line section.
- This scheme was impassive to variations in fault properties such as fault type, fault distance, degree of compensation, fault resistance and fault inception.
- Also, the computational burden was very less as scheme required only one cycle moving window data and least complex calculations, which makes this scheme fast. In addition, there is no need to change the threshold value for normal line and series compensated line.

COMPARISON

The concept of fault component integrated power introduced in Bolandi et al.(2014) has to change the threshold value by a multiplying by 0.5 factor for high resistance faults and by 10 factor for series compensated lines. Also, only one location and one compensation level of series compensation has been considered. Whereas, there is no need to change the threshold value for high Rf faults in uncompensated as well as series compensated system in proposed RPI based relaying.The new scheme of current differential protection in Dambhare et al. (2009) fails to respond fast for fault detection as it required more than 1-2 cycles for Rf more than 500 Ω. In comparison, proposed RPI scheme detects faults within half cycle time even in case of high resistance fault proving the fast operation in severe conditions. Results for high fault resistances are not discussed in algorithms of Abdelaziz et al. (2013) and Gupta & Tripathy (2014). Effect of series compensation is not considered in Suonan et al. (2011a) and Suonan et al. (2011b) with algorithms based on fault component integrated impedance approach whereas, proposed RPI based scheme works accurately even with normal line and fixed series compensation modes with various compensation locations and %compensation levels. Hence, RPI based scheme proves to be more reliable, sensitive and rugged with easy approach.

CONCLUSIONS

A new scheme based on RRPI has been proposed for fault detection, faulty phase identification and tripping of EHV transmission line with and without FSC compensation in this research paper. A wide range of fault properties have been applied to generate the training and testing data in order to improve the consistency of the scheme. Test simulation results show that the proposed scheme works accurately in broad range of fault conditions and detects the fault within half cycle time. There is no requirement to change the proposed relay threshold settings even with different FSC installation locations, %compensation levels, high fault resistances which have to be changed in conventional relay settings. It does not mal-operate for external faults. It is not disturbed by capacitive current and protection dynamics of FSC. RPI concept has never been applied before in any of the earlier conventional protection algorithms of lines, which make the proposed scheme distinct. The proposed online scheme, with least complexity and fast fault detection, is a potential protection solution to normal and fixed series compensated EHV transmission system.

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APPENDIX

Real transmission system line parameters for simulation:

- Thermal Limit of Quad Moose Conductor - 3000 A
- R1 = 0.0146 Ω/km, X1 = 0.2530 Ω/km, B1 = 4.5777 μ-mho/km (positive sequence values)
- R0 = 0.2479 Ω/km, X0 = 1.0001 Ω/km, B0 = 2.6345 μ-mho/km (zero sequence values)
- Bus Voltage - 400 kV at system frequency of 50 Hz
- Fault MVA level - 2.45 GVA
- Total MOV columns in parallel - 5+1 hot spare
- Reference Current per MOV column - 500 A

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