Impact of FACTS Controllerson Zone-I Protection of Distance Relay

G. Hemakumar Reddy, *PG Researcher*, MITS, Madanapalle, India
M.Ramesh, *Assistant Professor*, MITS, Madanapalle, India

Abstract**—This paper presents analytical and simulation results of the application of distance relays for the protection of transmission systems employing flexible alternating current transmission controllers. Firstly a detailed model of the Generalized FACTS controllers and its control is proposed and then it is integrated into the transmission system for the purposes of accurately simulating the fault transients. VSC-based multiline FACTS controllersemerged as a new opportunity to control two independent acsystems, the main constraints and limitations that are presentedto the conventional transmission-line protection systems need tobe investigated. In this paper, the impacts of VSC-based FACTScontrollers on distance relays while controlling the power flowof compensated lines are evaluated analytically and by detailedsimulations for different fault types.**

Index Terms**—Distance relay, flexible ac transmission systems(FACTS) controllers, generalized FACTS controllers, generalized interline power-flow controller(GIPFC), generalized unified power-flow controller (GUPFC),static compensator (STATCOM), static synchronous series compensator(SSSC).**

I. INTRODUCTION

CONTINUING pressure to minimize capital expenditure and the increasing difficulties involved in obtaining transmission rights of way have focused the attention of the utility community on the flexible alternating current transmission (FACTS) concept [1], [2] resulting in the initiation of studies and implementation programmes which are now well underway. However, the employment ofseries/shunt compensation of transmission lines by these devicescreates certain problems for their protective relays andfault locators using conventional techniques because of the rapidchanges introduced by the associated control actions in primarysystem parameters, such as line impedances and load currents.The most important singularity lays in the fact that the positive-sequence impedance measured by traditional distance relaysis no longer an indicator of the distance to a fault. The apparentimpedance seen by the relay is affected due to the uncertainvariation of series compensation voltage during the faultperiod [8]–[17].

Amongst the different types of FACTS controllers, UPFC is considered to be one of the most effective in the control of power flow. It comprises two back-to-back gate-turn-off thyristor (GTO) based voltage source converters (VSCs) connected by a dc -link capacitor., which consists of aseries and a shunt converter connected by a common dc-linkcapacitor, can simultaneously perform the function of transmission-line real/reactive power-flow control in addition to theUPFC bus voltage/shunt reactive power control. However, ifpower flows in more than one line need to be controlled simultaneously,UPFC seems out of its merits. Hence, multilinevoltage-source (VSC)-based FACTS controllers, such as an interlinepower-flow controller (IPFC) [5]; generalized interlinepower-flow controller (GIPFC) [6], [7]; and generalized unifiedpower-flow controller (GUPFC) [4] are introduced to controlthe power flows of multi-lines simultaneously. Multiline VSC-basedFACTS controllers can control different variables of the power system, such as the bus voltage and independent activeand reactive power flows of two lines by combining three ormore converters working together. So it extends the concepts ofvoltage and power-flow control beyond what is achievable withthe known two-converter UPFC controller.

Some research has been conducted to evaluate the performance of a distance relay for transmission systems with FACTScontrollers. In [8], an apparent impedance calculation procedurefor a transmission line with UPFC based on the power frequencysequence component is investigated; the studies includethe influence of setting UPFC control parameters and the operationalmode of UPFC. The work in [9] presents the operationof impedance-based protection relays in a power system containinga STATCOM; it is based on the steady-state analysis ofthe STATCOM and the protection relays. The work in [16] alsopresents steady-state analysis of the transmission-line protectionin the presence of series-connected FACTS devices. In [10],the performance of distance relays of the lines compensated bytwo types of shunt FACTS devices, SVC and STATCOM, areinvestigated. In [11], the impact of FACTS devices on the trippingboundaries of distance relay is presented. The works in[12] and [13] present a comprehensive analysis of the impact of Thyristor-Controlled Series Capacitor (TCSC) on the protectionof transmission lines and show that not only does the TCSC affectthe protection of its line, but the protection of adjacent lineswould experience problems. The studies in [14] indicate that theparameters of FACTS controllers and their location in the line(middle or line ends) have an impact on the trip boundary of adistance relay.

Fig. 1 shows the generic representation of a multiline VSC-basedFACTS controller. Different controllers are achieved bythe status of the dc switches, as Table I. According to this table,when all of the dc switches are closed, it represents a GUPFC[7]. SSSC1 and SSSC2 in Table I indicate the static synchronousseries compensators (SSSCs) configured in *Line 1* and *Line 2*,respectively.

If *Line 1* and *Line 2* are connected to separate buses in Fig. 1,then a GIPFC is established. In the GIPFC configuration, it ispossible to control the power flows of independent lines or evenlines that are physically close but operate at different voltagelevels.

R1 and R2 in Fig. 1 present a distance protective relay for*Line 1* and *Line 2,* respectively. In this paper, the behaviours R1 and R2 during a fault on the transmission lines are investigated for different FACTS controllers .It is worth noting that the impact of GIPFC on the protection of *Line 1* and *Line 2* could be regarded as the impact of an UPFC on relay and an SSSC on relay due to the fact that the *Line 1* and *Line 2* are separated from eachother and not parallel. Meanwhile, theimpact of GUPFC on the protective relays is more pronouncedthan GIPFC, because the current circulates in a loop comprisingof *Line 1* and *Line 2* during different faults.

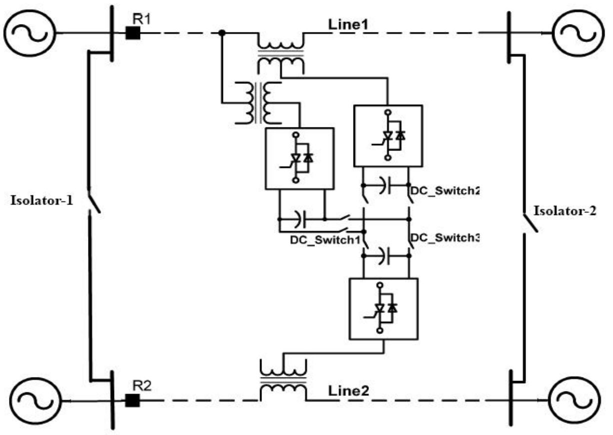

Fig.1.Simplified one-line diagram of generalized multiline FACTS controllers connectedto the middle of the transmission lines.

The objective of this paper is to analyse and investigate theimpact of different multiline VSC-based FACTS controllers onthe performance of impedance-based protection relays undernormal operation and fault conditions at different load powerflows. Different configurations of multilineVSC-based FACTScontrollers.

The controllers are modelled with detailed and sophisticatedtransient characteristics; the power system is designed withtraveling-wave transmission-line models and advanced modelsare used for protective relays [18].

This paper is organized as follows. Section II explains the impact of multiline VSC-based FACTS controllers on the apparent impedance seen by the protective relays. The analysis is comprehensive and considers different effects including the mutual impedance between the lines. Section-III presents sophisticated transient modelling of the series/shunt converters used in the simulations. Section IV introduces the sample network.Simulation results of the sample network for different FACTScontrollers.

II. MULTILINE VSC-BASED FACTS CONTROLLERS IMPACT ON APPARENT IMPEDANCE

The single-line diagram of the sample system used for theanalysis is shown in Fig. 2. It consists of two parallel lines andresembles the GUPFC configuration. In this figure, the GUPFCis connected to the middle of the line to include the series compensatorsin the fault loop. and are the series-injectedvoltages powered by the shunt converter, represented byimpedance and current source . If the converter losses areignored, then the active power drawn by the shunt leg is equalto the delivered power to lines 1 and 2.

The performance of relays and for different fault types, fault locations, and fault resistances is analysed to show the impact of different multiline VSC-based FACTS controllers on distance protection. Faults on *Line 1* at F point between K and H with the per-unit distance *x* from the relay location are considered. In this sense,*x* has a value between 0.5 and 1.0 for faults between K and H in the sample system. In Fig. 2,Z_L is the impedance of each line, and $V_G$is the voltage measured by R1 and R2 which is same for both relays.The positive-sequence network of sample system of Fig.2 is shown in Fig.3.

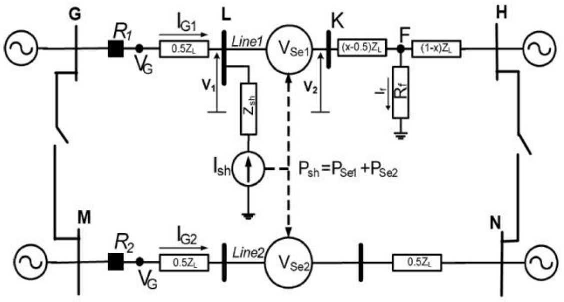

Fig. 2. Sample system

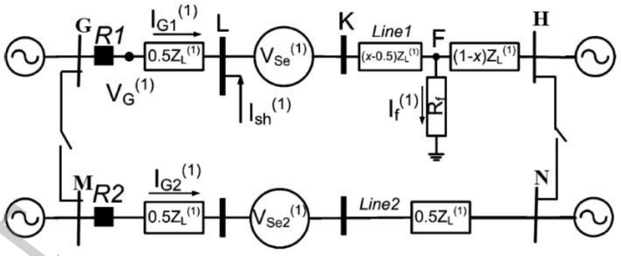

Fig.3.Positive-sequence network of the sample system

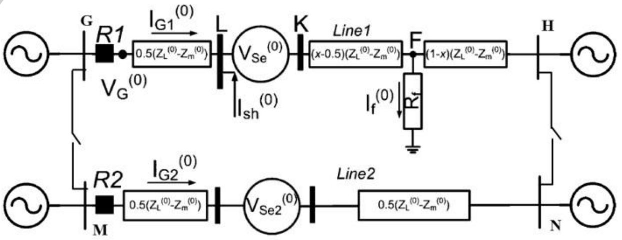

Fig.4.Zero-sequence network of the sample system

The negative-sequence network is the same as Fig. 3, except that the superscripts are changed 1 to 2. The zero-sequence network of the sample system of Fig. 2 is shown in Fig.4.$Z_m^{(0)}$is the zero-sequence mutual impedance between the ground wire(s) and the faulted phase conductor, per span of the lines.

The positive-sequence voltage at the relay point R1 can be expressed as follows:

$$V_G^{(1)} = I_{G1}^{(1)}\left(0.5Z_L^{(1)}\right) + \left(I_{G1}^{(1)} + I_{Sh}^{(1)}\right) \times \left((x-0.5)Z_L^{(1)}\right) + V_{Se1}^{(1)} + R_f I_f^{(1)} \qquad (1)$$

The positive-sequence mutual impedance of the lines$Z_m^{(1)}$ is negligible with respect to $Z_m^{(0)}$, so it is ignored in (1). Negative- sequence voltage$V_G^{(2)}$ is the same as (1), except that the superscripts are changed 1 to 2. Zero-sequence voltage is as follows:

$$V_G^{(0)} = I_{G1}^{(0)}\left(0.5\left(Z_L^{(0)} - Z_m^{(0)}\right)\right) + \left(I_{G1}^{(0)} + I_{sh}^{(0)}\right) \times \left((x-0.5)\left(z_L^{(0)} - Z_m^{(0)}\right)\right) + V_{Se1}^{(0)} + R_f I_f^{(1)} (2)$$

For a single-phase fault,the following equations can be used:

$$V_G^{(1)} + V_G^{(2)} + V_G^{(0)} = V_G (3)$$

$$I_G^{(1)} + I_G^{(2)} + I_G^{(0)} = I_{G1} (4)$$

Using the previous equations,we have

$$V_G = I_{G1}\left(xZ_L^{(1)}\right) + I_{G1}^{(0)}\left[x\left(Z_L^{(0)} - Z_L^{(1)} - Z_m^{(0)}\right)\right] + I_{Sh}(x-0.5)Z_L^{(1)} + I_{sh}^{(0)}[(x-0.5)(Z_L^{(0)} - Z_L^{(1)} - Z_m^{(0)})] + V_{Se1} + R_f I_f (5)$$

A.Single-phase fault

For a single-phase fault on line 1,the apparent impedance seen by relay R1 is as follows:

$$Z_{R1} = \frac{V_G}{I_{G1}+\left(\frac{Z_L^{(0)}-Z_L^{(1)}}{Z_L^{(1)}}\right)I_{G1}^{(0)}} = \frac{V_G}{I_{R1}}.(6)$$

Using (5) in (6), we have

$$\mathrm{Z_{R1}}{=}xZ_L^{(1)}\text{-}xZ_m^{(0)}\frac{I_{G1}^{(0)}}{I_{R1}}+\frac{I_{sh}}{I_{R1}}(x\text{-}0.5)Z_L^{(1)}+\frac{I_{sh}^{(0)}}{I_{R1}}(x\text{-}0.5)(Z_L^{(0)}\text{-}Z_L^{(1)}\text{-}Z_m^{(0)})+\frac{V_{se1}}{I_{R1}}+R_f\frac{I_f}{I_{R1}}(7)$$

From (7), we see that the apparent impedance seen by thetraditional distance relay R1 during a single-phase fault when applied to the transmission system employing GUPFC as one of the multiline VSC-based FACTS controllers, has six components:

1)$xZ_L^{(1)}$: Positive-sequence impedance from the relay point to the fault point, which should be the correct value for the distance relay;

2)$xZ_m^{(0)}({}^{I_{G1}^{(0)}}/_{I_{R1}})$: This part is the impact of zero-sequence mutual impedance of the transmission lines, which can be treated the same as the uncompensated lines;

3)$\frac{I_{sh}}{I_{R1}}(x\text{-}0.5)Z_L^{(1)}$: The shunt current injected by the shunt converter of the GUPFC, which has a direct impact on the apparent impedance.

4)$\frac{I_{sh}^{(0)}}{I_{R1}}(x\text{-}0.5)(Z_L^{(0)}\text{-}Z_L^{(1)}\text{-}Z_m^{(0)})$: This part relates to the impact of zero-sequence current injected by the shunt converter of the GUPFC; in practice, one side of the shunt transformer of the GUPFC often has a delta connection, so there is no zero-sequence current injected by this shunt leg, and this part can be neglected;

5) $\frac{V_{se1}}{I_{R1}}$: The injected series voltage of the GUPFC has a direct impact on the apparent impedance;

6) $R_f\frac{I_f}{I_{R1}}$: The last part of the apparent impedance is caused by fault resistance.

For a single-phase fault on *Line 2*, the analysis will be the same. The apparent impedance seen by R2 for a single-phase fault is represented by

It means that the impact of GUPFC on relay R2 is only dueto the injected series voltage of GUPFC and the contribution of GUPFC to the fault current. In other words, the impact of injected shunt currentI_{sh} on$Z_{R2}$is negligible for solid faults. However,I_{sh}directly affects Z_{R1}even ifR_f=0. This is a major difference between (7) and (8). It can also be seen from (8) that the series-injected voltage is directly added to the apparent impedance$Z_L^{(1)}$;hence increasing the apparent impedance seen by the relay.

If the GUPFC in the sample system is replaced by an IPFC,then the injected shunt currentI_{sh} will be zero and the effect of the IPFC on the apparent impedance is only through the seriesinjected voltagesV_{se1}orV_{se2}.

B. Phase-to-Phase Fault

The apparent impedance seen by *R1* for a phase-to-phase fault,such as *A-B*, is expressed as

$$\mathrm{Z_{R1(A\text{-}B)}}=\frac{V_A-V_B}{I_A-I_B}=\frac{V_{relay}}{I_{relay}}=\frac{V_G^{(1)}-aV_G^{(2)}}{I_G^{(1)}-aI_G^{(2)}}(9)$$

Where $1\angle120^0$ =-0.5+j0.886.V_A,V_B,$I_A$and $I_B$are the voltages and currents of phases A and B at the relay point,respectively.Using (1),we have

$$V_G^{(1)} - aV_G^{(2)}{=}xZ_{L1}^{(1)}\left(I_{G1}^{(1)} - aI_{G1}^{(2)}\right) + \left(I_{Sh}^{(1)} - aI_{Sh}^{(2)}\right) (x-0.5)Z_{L1}^{(1)} + \left(V_{Se1}^{(1)} - aV_{Se2}^{(2)}\right) + (I_f^{(1)} - aI_f^{(2)})R_f \qquad (10)$$

R_f is the fault resistance between two phases in (10).
Hence,the apparent impedance for a phase-to-phase (A-B) fault is

$$Z_{R1(A-B)} = xZ_{L1}^{(1)} + \frac{\left(I_{Sh}^{(1)} - I_{Sh}^{(2)}\right)}{I_{relay}}(x-0.5)Z_{L1}^{(1)} + \frac{(V_{Se1}^{(1)}-aV_{Se1}^{(2)})}{I_{relay}} + \frac{(I_f^{(1)}-aI_f^{(2)})}{I_{relay}}R_f(11)$$

From (11), we can conclude that during a phase-to-phase fault, the apparent impedance seen by R1 is composed of four parts: the first is positive-sequence impedance from the relay point to fault point, which should be the correct value for the relay; the second part is the impact of shunt converter on the apparent impedance and depends upon the difference between the positive- and negative-sequence currents injected by the shunt leg; the third is proportional to the difference between the positive- and negative-sequence voltages injected by the seriesconverter; and the last part of the apparent impedance is caused by the fault resistance. For a solid phase-to-phase fault, the impact of GUPFC on the apparent impedance is expressed by $(I_{sh}^{(1)} - aI_{sh}^{(2)})/(I_{relay})$ and$(V_{se1}^{(1)} - aV_{se1}^{(2)})/(I_{relay})$, which are less significant with respect to a single-phase fault. In other words, the impact of GUPFC on the apparent impedance is more pronounced for single-phase faults than phase-to-phase faults. For R2 , the shunt converter contribution to the apparent impedance is not available so the impact is only due to the series part $(V_{se1}^{(1)} - aV_{se1}^{(2)})/(I_{relay})$.

III. CONVERTER CONTROL SYSTEM

FACTScontrollers has many possible operating modes, it isanticipated that the shunt converter will generally operate in automaticvoltage-control mode and the series converter will typicallybe in automatic power-flow control mode. Accordingly,block diagrams are shown in Fig. 5(a) and (b), giving greater detailof the control schemes for each converter operating in thesemodes. The control schemes assume that series and shunt convertersgenerate output voltage with controllable magnitude andangle, and that the dc bus voltage will be held substantially constant[19].

The automatic power-flow control for the series converter isachieved by means of a vector-control scheme that regulates thetransmission-line current, using a synchronous reference framein which the control quantities appear as dc signals in the steadystate. The appropriate real and reactive current components aredetermined for a desired and , compared with the measuredline currents, and used to derive the magnitude and angleof the series converter voltage. The series-injected voltage limiterin the forward path of this controller takes practical limitson series voltage into account. This is an important point in analysing the impact of FACTS controllers on the performance of distancerelay, ignoring the role of the “series injected voltage limiter”block in Fig. 5(b), overestimating the impact of FACTS,and leading to unrealistic exaggerated results, creating overratedconcerns for utilities.

A vector-control scheme is also used for the shunt converter.In this case, the controlled current is the current delivered to theline by the shunt converter. In this case, however, the real and reactive components of the shunt current have a different significance. The reference for the reactive current is generated by an outer voltage-control loop, responsible for regulating the ac bus voltage and the reference for the real power-bearing current is generated by a second voltage-control loop that regulates the dc bus voltage. In particular, the real power negotiated by the shunt converter is regulated to balance the dc power from the series converter and maintain a desired bus voltage. The dc voltage reference $V_{\text{dc ref}}$ may be kept substantially constant. For the shunt converter, the most important limit is the limit on shunt reactive current, nominated by the “shunt reactive current limiter” block in Fig. 5(a), as a function of the real power being passed through the dc bus. This prevents the shunt converter current reference from exceeding its maximum rated value. The current limiter in the shunt control system is used to restrict $\sqrt{I_{dshunt}^2 + I_{qshunt}^2}$in a specified value. In normal operating conditions, active current(I_{dshunt})is very small. So is approximately equal toI_{qshunt}. However, when a fault occurs on the line,I_{dshunt} is increaseddue to the power system unbalance condition. In contrasttoI$_{\text{qshunt}}$,I$_{\text{dshunt}}$ is not controllable. Therefore, in orderto limit $\sqrt{I_{dshunt}^2 + I_{qshunt}^2}$,I$_{\text{qshunt}}$should be decreased.

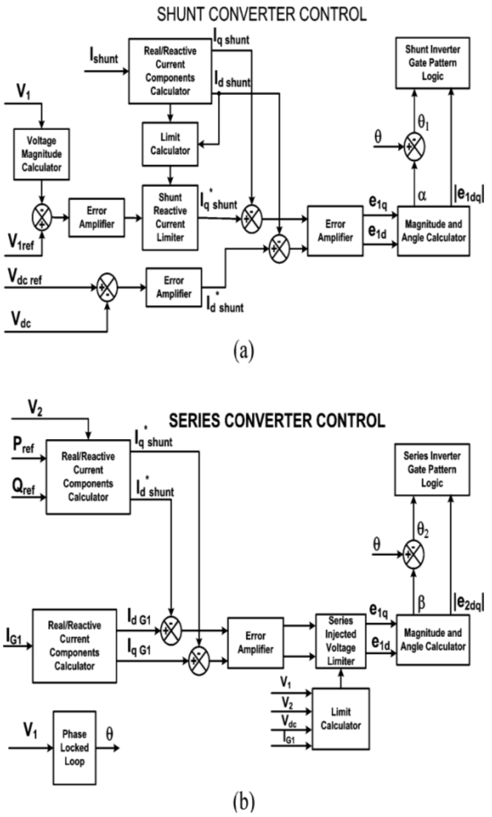

Fig. 5. Control systems used for converters. (a) Shunt converter controlsystem. (b) Series converter control system.

The control block diagrams shown in Fig. 5(a) and (b) areonly a small part of the numerous control algorithms that areneeded for all of the operating modes of the GUPFC, andfor protection and sequencing. The control system typicallyincorporates many sophisticated elements that comprise thedynamics of a multiline FACTS controller [24].

IV. SAMPLE SYSTEM

The sample system used for simulation is as Fig.2. It is simulatedin the *MATLAB/Simulink* environment using the *SimPowerSystems*toolbox and discrete modelling with detailed representationof the components [23]. The 300 km, 500 kV double-circuittransmission lines and the sources have the followingpositive- and zero-sequence impedances:

- $Z_L^{(1)}$=0.02546+J0.352Ω/km,$Z_L^{(0)}$==0.3864+J1.5556Ω /km,
- $Z_G^{(1)}$==1.7431+J 19.424Ω, $Z_G^{(0)}$==2.6147+J4.886Ω,
- $Z_H^{(1)}$==0.8716+J 9.712Ω, $Z_H^{(0)}$==1.3074+J 2.443Ω,
- Loadangle between the sources is 20^0.

V. SIMULATION RESULTS

The simulations are performed on the sample system ofFig. 2. In analyzing the impact of different FACTS controllers(GUPFC,GIPFC,UPFC and IPFC) on the performance of distancerelay, the reference values of the active and reactive powersand of the transmission lines, associated with the seriesconverters [Fig. 5(b)] and the reference voltage valueof the shunt converter are fixed at the same values, so the powerflows and the related bus voltage are the same for the normalcases. After the fault, the power flows and the controlled busvoltage change, hence the associated series/shunt controllersattempt to bring them to pre-fault values, resulting differentimpacts on the apparent impedance seen by the relay based onthe configuration of the related FACTS controller.

A.Relay Performance for a single phase fault (A-G)

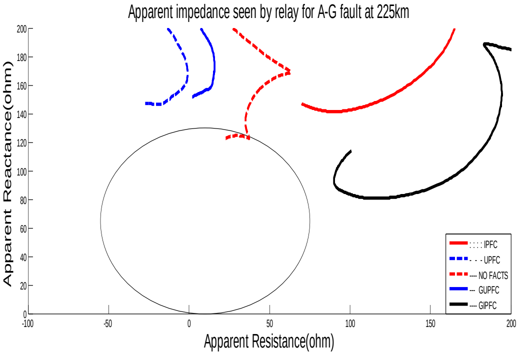

Fig.6.Apparent impedance seen by relay R1 for single-phase fault at 225km for different FACTS controllers

Fig.6 shows the apparent impedance seen by relay in the sample system of Fig.2 for a single-phase fault (A-G) at 225 km (75% of the 330 km line) from the relay with Zone I setting =0.8*300 =240 km for different FACTS controllers. It can be seen that the trajectories of apparent impedances do not enter the *Zone I* characteristics for GUPFC/GIPFC/UPFC/IPFC. It can be deduced that GUPFC/GIPFC/UPFC/IPFC caused the relay to under-reach (i.e., not to detect the fault at *Zone I*), for single-phase (A-G) fault.

B. Relay Performance for Two-Phase Faults (A-B)

Fig.7 shows the apparent impedance seen by relay in thesample system of Fig. 2 for a two-phase fault (A -B) at 225 km(75% of the 300 km line) from the relay with *Zone I* setting = 0.8*300 = 240 km for different FACTS controllers. It can beseen that the trajectories of apparent impedances do not enterthe *Zone I* characteristics for GUPFC/UPFC, while thetrajectory does enter the circle for GIPFC/IPFC. It can be deduced thatGUPFC/UPFC caused the relay to under-reach (i.e., not to detect the fault at *Zone I*), while the impact of GIPFC/IPFC is not remarkable.

C. Relay Performance for Two-Phase-to-Ground Faults

Fig.8. shows the case for a two-phase-to-ground fault (*ABG*) at 225 km from for different relay measuring

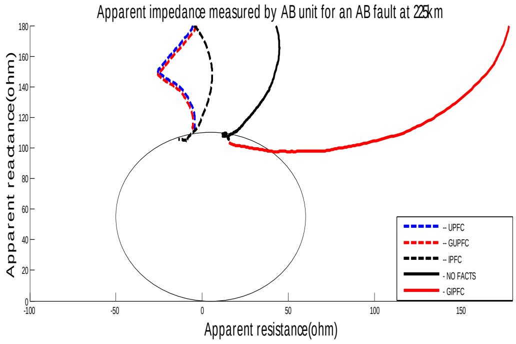

Fig.7.Apparent impedance seen by R_1 for a phase-to-phase fault at 225 km.

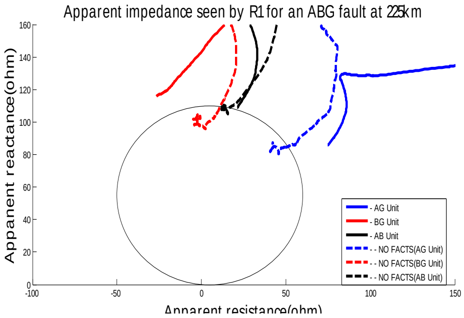

Fig.8.Apparent impedance seen by different measuring units of the relay foran *ABG* fault at 225 km with GUPFC.

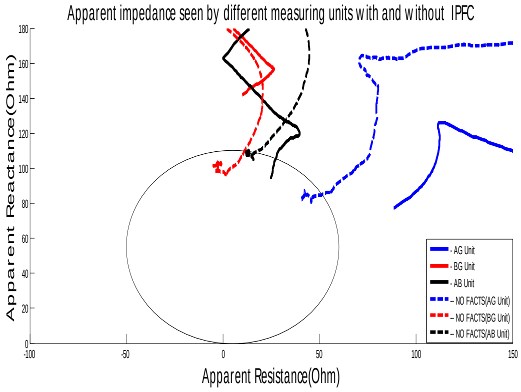

Fig.9.Apparent impedance seen by different measuring units of the relay for an *ABG* fault at 225 km with IPFC.

units(i.e., A-B are responsible for monitoring phase-to-phasefaults, and A-Gand B-G are dedicated to single-phase faults. It is well worth remindingthat the conventional full-scheme distance relays havesix measuring units, that is, three for single-phase faults (A-G ,B-G and C-G) and three phase-to-phase measuring units (A-B ,B-C and C-A). The other fault types are detected by a combinationof these six measuring units.

As can be deduced from Fig.8, the impact of GUPFC for*ABG* faults is less severe than the single-phase faults. Despitethe fact that the A-B unit does not cross the trip boundary, itis still less affected than the single-phase measuring units (A-Gand B-G).

If GUPFC is replaced by IPFC (i.e., the shunt converter is putout of action), the A-B measuring unit enters the circleand the relay detects the fault at *Zone I* according to Fig.9.This indicates that in the case of IPFC, the relay is less affectedfor two-phase-to-ground faults.

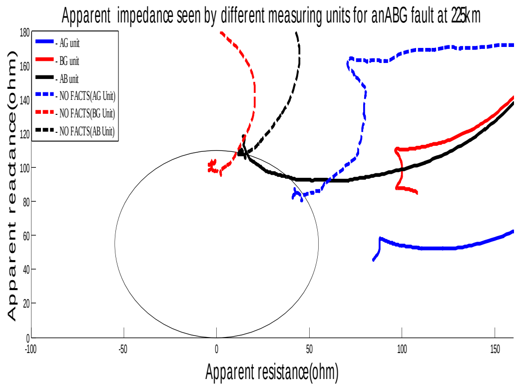

Fig.10. Apparent impedance seen by different measuring units of the relay for an *ABG* fault at 225 km with GIPFC.

This case can be justified by thefact that the IPFC does not have a shunt converter to controlthe bus voltage that it is attached to (V1 in Fig. 2), so there isless intervention from the multiline FACTS controllers on thenatural behaviour of the power system during faults.

If GUPFC is replaced by GIPFC (i.e, two lines are connected to two separate buses), the A-B measuring unit enters the circle and the relay detects the fault at *Zone I* according to Fig.10.This indicates that in the case of IPFC, the relay is less affected for two-phase-to-ground faults. This case can be justified by the fact that the GIPFC does have a shunt converter to control the bus voltage that it is attached to bus 1 only.

E. Impact of Limiters of the Series and Shunt Converters on the Apparent Impedance

As mentioned in Section III, the limiters in Figs. 5(a)and(b) have an extraordinary effect on the performance evaluation of the relay.

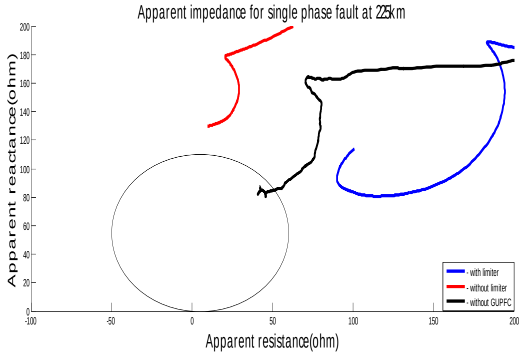

Fig.11. Apparent impedance for an A-G fault at 225 km with and without a “shunt reactive current limiter” and “series injected voltage limiter” blocks.

The simulations are performed by bypassing them for comparison. As already mentioned, the impact of the shunt converter limiter is more pronounced. Fig.11shows the apparent impedance for a single-phase fault at 225 km with/without implementing “shunt reactive current limiter” and “series injected voltage limiter” blocks as in Fig. 5. The overall result is that the relay under-reaches when GUPFC is used for system compensation, with/without limiters. Bypassing the limiters in this case has a hybrid influence on the apparent impedance. As can be deduced from Fig.11, there is no remarkable difference between the system with series and shunt limiters and the system without both of them. This means the deficiency of neglecting the shunt limiter is compensated by omitting the series limiter, henceforth, the overall effect is not so appreciable.

Fig.12 shows the apparent impedance seen by R1 for a single-phase fault at 225km on line 1 compensated by GUPFC with/without limiter on the shunt converter.Ascasn be deduced from this figure, negligence of the “shunt reactive current limiter” block in fig 5(a) causes the relay measuring system to overestimate the effect of GUPFC

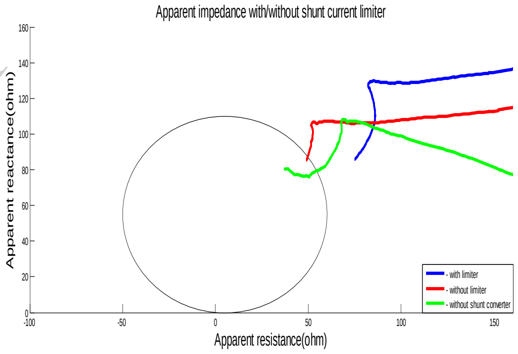

Fig.12.Impact of “shunt reactive current limiter” block on the measured apparent impedance.

Meanwhile, the detailed and accurate modelling of the GUPFC dynamics and practical constraints lead to a more realistic result and demonstrate the correct operation of the relay by indicating that the apparent impedance trajectory crosses the trip boundary. As Fig. 12 shows, the omission of the shunt limiter means there is no bound on the GUPFC injecting shunt current during the fault.

VI. CONCLUSION

In this paper, it is shown that multiline VSC-based FACTScontrollers, which are used to simultaneously control the activeand reactive power flows of multi-lines, have a remarkable impacton conventional distance protection of transmission linesdue to the rapid changes introduced by the associated controlactions in primary system parameters such as line impedancesand load currents. GUPFC, IPFC, and UPFC are analysed assamples of multiline FACTS controllers. The following pointsare concluded from this study.

- The GUPFC impact on the apparent impedance measuredby the relay is higher reactance/resistance. In other words, GUPFC causes the relay to under-reach.
- The GIPFC impact on the apparent impedance is less compared to other FACTS controllers. It is justified that no circulating currents in GIPFC during the faults.
- Detailed and accurate modelling of the GUPFC dynamicsand imposing practical constraints lead to a more realisticresult and demonstrate the correct operation of the relay forfaults at *Zone I*.
- In the case of IPFC, the relay is less affected for differentfaults, especially, two-phase-to-ground faults. This is dueto the fact that the IPFC does not have a shunt converter tocontrol the bus voltage that it is attached to, so there is lessintervention from the multiline FACTS controllers on thenatural behaviour of the power system during faults.
- The impact of GUPFC/GIPFC is the most severe and the impactof IPFC is the least. This is due to the intervention of theshunt controller in the case of GUPFC/GIPFC/UPFC.
- Negligence of the "shunt reactive current limiter" block in the shunt converter control system causes the relay measuring system to overestimate the effect of GUPFC/GIPFC.
- Negligence of the "shunt reactive current limiter" and "series injected voltage limiter" blocks in shunt and series converter control systems there is no remarkable difference between the system with/without series and shunt limiters.
- In the case of GIPFC, the relay is less affected for different faults. This is due to the fact that GIPFC does have a shunt converter to control the bus voltage at olny one line and also no circulating currents during the faults.

REFERENCES

[1] N. G. Hingorani and L. Gyugyi, *Understanding FACTS:Concepts andTechnology of Flexible AC Transmission Systems*. Piscataway, NJ:IEEE Press, 2000.

[2] Y. H. Song and A. T. Johns, *Flexible AC Transmission Systems*. New York: IEEE Press, 1999.

[3] K. K. Sen, "SSSC—Static synchronous static compensator: Theory,modeling, and applications," *IEEE Trans. Power Del.*, vol. 13, no. 1,pp. 241–246, Jan. 1998.

[4] Static Synchronous Series Compensator (SSSC), CIGRE Brochure,Working Group B4.40 no. 371, Feb. 2009.

[5] B. Fardanesh, B. Shperling, E. Uzunovic, and S. Zelingher, "Multi-converterfacts devices: The generalized unified power flow controller(GUPFC)," in *Proc. IEEE Power Eng. Soc. Summer Meeting*, Jul.16–20, 2000, vol. 2, pp. 1020–1025.

[6] L. Gyugyi, K. K. Sen, and C. D. Schauder, "Interline power flowcontroller concept: A new approach to power flow management intransmission systems," *IEEE Trans. Power Del.*, vol. 14, no. 3, pp.1115–1123, Jul. 1998.

[7] R. L. Vasquez-Arnez and L. C. Zanetta, Jr., "Multiline power flow control:An evaluation of the GIPFC (generalized Interline power flowcontroller)," presented at the 6th Int. Conf. Power Systems Transients,Montreal, QC, Canada, June 19–23, 2005.

[8] Khederzadeh, M.; Ghorbani, A., "Impact of VSC-Based Multiline FACTS Controllers on Distance Protection of Transmission Lines" Power Delivery, IEEE Trans.,Volume : PP , no:99 On page(s): 1 ISSN :0885-8977,oct. 2011

[9] R. L.Vasquez-Arnez and L. C. Zanetta, Jr., "A novel approach for modelingthe steady-state vsc-based multiline FACTS controllers and theiroperational constraints," *IEEE Trans. Power Del.*, vol. 23, no. 1, pp.457–464, Jan. 2008

[10] M. Khederzadeh, "The impact of FACTS device on digital multifunctional protective relays," in *Proc. IEEE/PES Transmission and Distribution Conf. and Exhib. 2002: Asia Pacific*, vol. 3, Oct. 6–10, 2002, pp. 2043–2048..

[11] X. Zhou, H. Wang, R. K. Aggarwal, and P. Beaumont, "Performanceevaluation of a distance relay as applied to a transmission system withUPFC," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1137–1147, Jul.2006.

[12] K. El-Arroudi, G. Joos, and D. T. McGillis, "Operation of impedanceprotection relays with the STATCOM," *IEEE Trans. Power Del.*, vol.17, no. 2, pp. 381–387, Apr. 2002.

[13] T. S. Sidhu, R. K. Varma, P. K. Gangadharan, F. A. Albasri, and G.R. Ortiz, "Performance of distance relays on shunt—FACTS compensatedtransmission lines," *IEEE Trans. Power Del.*, vol. 20, no. 3, pp.1837–1845, Jul. 2005.

[14] P. K. Dash, A. K. Pradhan, G. Panda, and A. C. Liew, "Adaptive relaysetting for flexible AC transmission systems (FACTS)," *IEEE Trans.Power Del.*, vol. 15, no. 1, pp. 38–43, Jan. 2000.

[15] M. Khederzadeh and T. S. Sidhu, "Impact of TCSC on the protection oftransmission lines," *IEEE Trans. Power Del.*, vol. 21, no. 1, pp. 80–87,Jan. 2006.

[16] T. S. Sidhu and M. Khederzadeh, "TCSC impact on communication—Aided distance protection schemes and its mitigation," *Proc.Inst. Elect. Eng. C, Gen., Transm. Distrib.*, vol. 152, no. 5, pp.714–728, Sep. 2005.

[17] M. Khederzadeh, "The impact of FACTS device on digital multifunctionalprotective relays," in *Proc. IEEE/Power Eng. Soc. Transm. Distrib.Conf. Exhibit.*, Oct. 6–10, 2002, vol. 3, pp. 2043–2048.

[18] T. S. Sidhu and M. Khederzadeh, "Series compensated line protectionenhancement by modified pilot relaying schemes," *IEEE Trans. PowerDel.*, vol. 21, no. 3, pp. 1191–1198, Jul. 2006.

[19] P. K. Dash, A. K. Pradhan, G. Panda, and A. C. Liew, "Digital protectionof power transmission lines in the presence of series connectedFACTS devise," in *Proc. IEEE Power Eng. Soc. Winter Meeting*, Jan23–27, 2000, vol. 3, pp. 1967–1972.

[20] D. L. Waikar, S. Elangovan, and A. C. Liew, "Fault impedance estimation algorithm for digital distance relaying)," *IEEE Trans. Power Delivery*,vol. 9, no. 3, pp. 1375–1383, Jul. 1994.

[21] D. Novosel, A. Phadke, M. M. Saha, and S. Lindahl, "Problems andsolutions for microprocessor protection of series compensated lines," in*Proc. Int. Elect. Eng. Conf. Develop. Power Syst. Protect.*,Mar. 25–27,1997, pp. 18–23.[18] G. Benmouyal, "Removal of DC-offset in current waveforms using
digital mimic fltering," *IEEE Trans. Power Del.*, vol. 10, no. 2, pp.621–630, Apr. 1995.

[22] C. D. Schauder, L. Gyugyi, M. R. Lund, D. M. Hamai, T. R. Rietman,D. R. Torgerson, and A. Edris, "Operation of the unified power flowcontroller (UPFC) under practical constraints," *IEEE Trans. PowerDel.*, vol. 13, no. 2, pp. 630–636, Apr. 1998.

[23] SimPowerSystems Toolbox Ver. 5.1, for Use With Simulink, User'sGuide 2009. Natick, MA, The MathWorks, Inc..

[24] Y. Liao and S. Elangovan, "Digital distance relaying algorithm for firstzoneprotection for parallel transmission lines," *Proc. Inst. Elect. Eng.C, Gen. Transm. Distrib.*, vol. 145, no. 5, pp. 531–536, Sep. 1998.