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Firefly Algorithm Based Optimal PI Controller for a Monopolar HVDC Transmission System Feeding a Weak AC Network with Hybrid Reactive Power Compensators

S. Seenivasan[*] and S. Singaravelu[*]

ABSTRACT

This paper presents firefly algorithm based optimal proportional integral (PI) controller for a line commutated converter (LCC) - HVDC transmission system feeding a weak AC network with hybrid reactive power compensators (RPC's) at the inverter AC side. The hybrid compensator is formed by equally mixing of fixed capacitor (FC) with any one of the following compensators: synchronous compensator (SC); static var compensator (SVC); static synchronous compensator (STATCOM). The HVDC transmission system model is simulated using Matlab. Under various fault conditions, the transient performances of hybrid RPC's (FC+SC, FC+SVC and FC+STATCOM) are investigated and the results are compared with the performance of the SC, SVC and STATCOM to focus the supremacy of the hybrid compensators. The simulation results confirm that the equal mix of FC and STATCOM has a steady and fastest response. The outcomes also demonstrate the superiority of the firefly algorithm based optimal PI controller over the conventional PI controller. At the inverter AC side, the harmonic estimation is also carried out under steady state operation to declare the quality of power supply.

Keywords: Monopolar HVDC, Weak AC system, Hybrid RPC's. PI controller, Firefly algorithm

1. INTRODUCTION

Due to the rapid improvements in the voltage, power carrying capacity and length of transmission lines, the HVDC power transmission technology is now emerging and attracted the attention of many researchers [1]. The behaviour of the HVDC system plays ever greater roles in the performance of entire AC/DC power systems. It is essential to understand the mechanisms of the interactions between an HVDC system and an AC network so the HVDC system can be operated in a manner that enhances the stability of the entire power grid. The importance of this interaction largely depends on the strength of the AC system at the converter bus [2], which is mostly expressed by the short circuit ratio (SCR). The following SCR values [3] can be used to classify AC systems: (A) SCR >3 for a strong system, (B) $2 \leq \text{SCR} < 3$ for a weak system, (C) SCR < 2 for a very weak system.

In order to know the interaction between AC network and HVDC system, a lot of work has been done until now. The voltage stability associated phenomena [4] at HVDC terminals feeding weak AC network and solutions for eradicating the risks of voltage collapse and for evading control induced oscillations were discussed. The Nelson River HVDC system is analyzed with new synchronous compensators in [5] and also tinted planning requirements and synchronous compensators specification to optimize power delivery by the DC links. An analysis of the dynamic performance of HVDC systems [6] connected to a weak AC

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system is carried out for various exciter characteristics of synchronous machines connected to the converter bus. The direct transient stability margin (TSM) prediction method [7] based on the extended equal area criterion is used for the integration of HVDC transmission system and SVC into the power system. The usage of STATCOM at the inverter end of a classical HVDC system for the reactive power support is deliberated in [8]. The coordination between STATCOM and HVDC classic link feeding a weak AC network is examined in [9] with two different control technique during various fault conditions.

Analysis of the fault recovery performance and suppression of dynamic overvoltage (DOV) criterion of an HVDC system feeding a weak AC network [10] is carried out with a fixed capacitor (FC), SC, thyristor controlled reactor (TCR), thyristor switched capacitor (TSC), metal oxide varistor (MOV), series capacitor device (SCD). The DC power recovery and suppression of temporary overvoltage (TOV) of an HVDC system feeding a very weak AC network [11], [12], have been discussed. To make the analysis complete, it is highly essential to consider the suppression of TOV and fault recovery for an HVDC system feeding a weak AC network. Therefore, in this simulation work both the fault recovery performance as well as suppression of TOV during various transient fault conditions has been carried out for an HVDC system connected to a weak AC network with the hybrid RPC's: FC+SC, FC+SVC and FC+STATCOM. These results are compared with the performance of SC, SVC and STATCOM. The harmonics investigation is also carried out under steady state to assure the quality of power supply on the inverter AC side.

The PI controller with fixed gain used for the rectifier and the inverter controllers of HVDC system causes instability due to deficiency in tuning its gain for various abnormal operating conditions. To overcome this drawback intelligent technique has been introduced for apt tuning of the PI controller parameters [13], [14], [15], [16]. However, in all those tuning methods the principal signals used to fix the PI gains of the rectifier and the inverter current controllers are current error and its derivative. On the other hand, for the inverter gamma controller, the gamma error and its derivative are used. In this paper, minimization of the rectifier and the inverter DC power errors are considered as an objective function which is achieved by the firefly optimization algorithm, to fix the PI gains of the respective PI controller. To demonstrate the effectiveness of the firefly algorithm based optimal PI controller on transient performance of HVDC system, it has been compared with conventional PI controller.

2. MODELLING OF MONOPOLAR HVDC TRANSMISSION SYSTEM

A line commutated converter based monopolar HVDC system of 500kV, 2kA, 1000MW feeding a strong AC network [17], in which inverter side AC network is replaced by a weak AC network as shown in the Figure 1. The rectifier side AC system of 500kV, 5000MVA, 60Hz is connected to the inverter side AC system of 345kV, 2500MVA, 50Hz through an HVDC network. Generally, the AC system is represented by damped LLR equivalents. The Passive filters of 450MVAr are connected on the source side to eliminate the 11th and 13th (the double tuned type) order and above 24th (second order high pass filter) order current

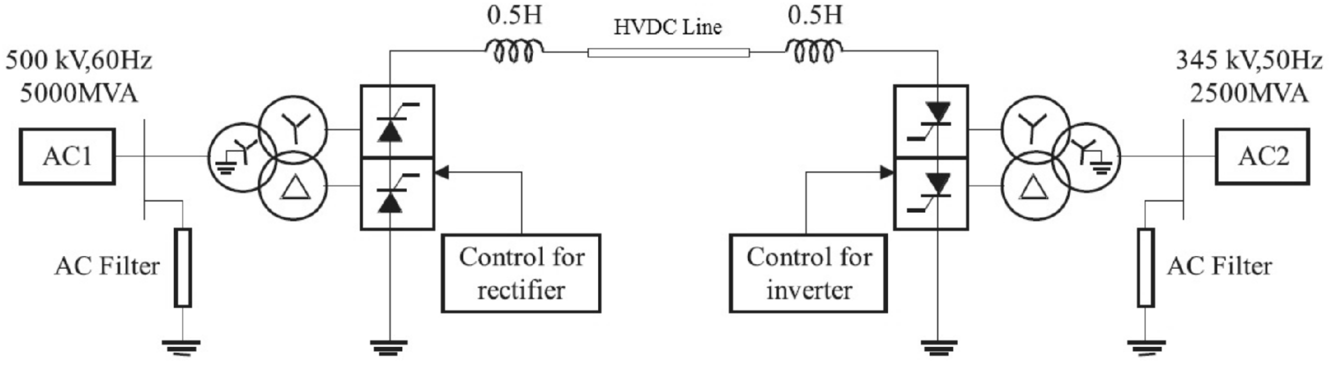

Figure 1: Monopolar HVDC Transmission System Model Feeding a Weak AC Network

harmonics and synchronous or static compensator or fixed capacitor with synchronous or static compensator is used (150MVAr) for reactive power compensation. The rectifier and the inverter are 12-pulse converters.

The DC network model consists of a smoothing reactor for the rectifier and the inverter bridges, a passive filter of double tuned type to mitigate the 12th and 24th order DC voltage harmonics and the DC line. The DC link of 1500 km is modelled as a distributed parameter line model with lumped losses. The rectifier is equipped with a current controller to maintain the DC system current constant. The inverter is provided with a current controller to maintain the DC system current constant and a constant extinction angle or gamma controller. The reference current for the current controllers is obtained from the master controller output through the voltage dependent current order limiter (VDCOL). In order to protect the rectifier and the inverter DC protection functions are implemented in each converter. In the inverter side AC network, the following six reactive power compensator options are studied.

2.1. Synchronous Compensator

The SC model of 150MVAr shown in Figure 2 is represented with the simplified synchronous machine block which models, both the electrical and mechanical characteristics of a simple synchronous machine. The SC uses the solid static excitation system.

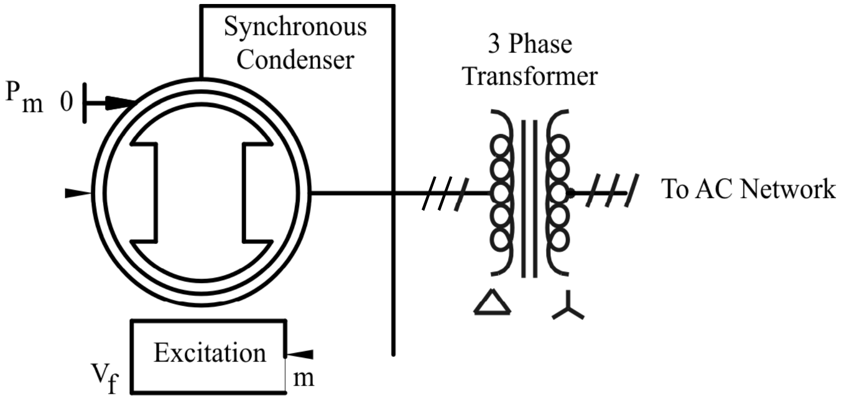

Figure 2: Schematic of SC

2.2. Static Var Compensator

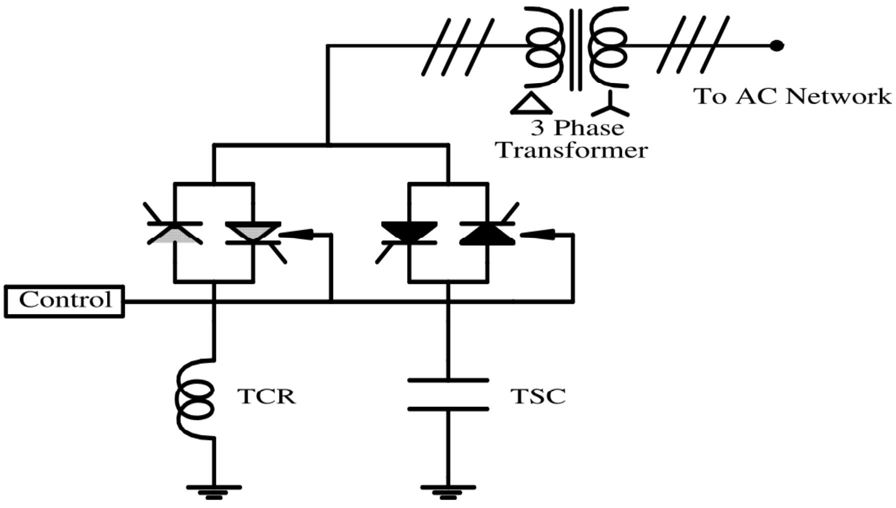

Figure 3: Schematic of SVC

A 150MVAr SVC shown in Figure 3 regulates voltage on a 345kV system. The SVC consists of a 345kV/16kV, 168MVA coupling transformer, one 60MVAr TCR bank and one 180MVAr TSC connected to the secondary side of the transformer. Switching the TSC in and out allows a continuous variation of the secondary reactive power from zero to 180MVAr capacitive, whereas phase control of the TCR allows a continuous variation from zero to 60 MVAr inductive.

2.3. Static Synchronous Compensator

The STATCOM shown in Figure 4 is located at the inverter side of the HVDC link and has a rating of ±150MVAr. This STATCOM is a typical simple PWM voltage source converter (VSC). It consists of a 6 pulse VSC inverter and a series connected capacitors which act as a variable DC voltage source. Based on a VSC, the STATCOM regulates system voltage by absorbing or generating reactive power.

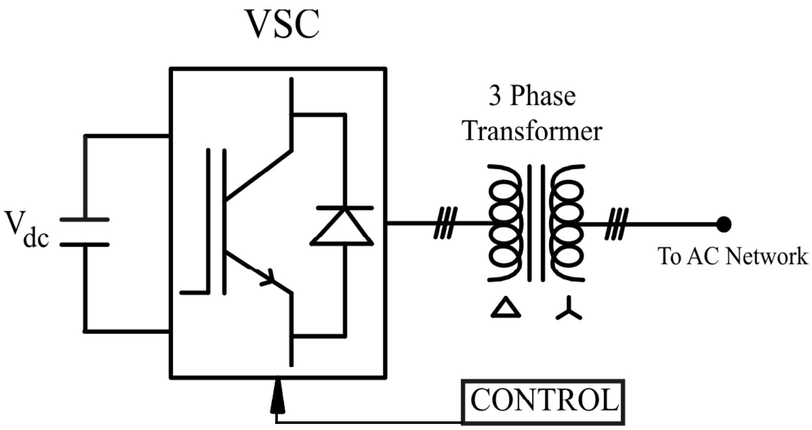

Figure 4: Schematic of STATCOM

2.4. An Equal Mix of FC and SC

The FC (75MVAr) and SC (75MVAr) are connected to the inverter bus in this scheme. In steady state the FC and SC each supply 75MVAr.

2.5. An Equal Mix of FC and SVC

The FC (75MVAr) and SVC (-90MVAr, +30MVAr) are connected to the inverter bus in this scheme. In steady state the FC and SVC each supply 75MVAr.

2.6. An Equal Mix of FC and STATCOM

The FC (75MVAr) and STATCOM (±75MVAr) are connected to the inverter bus in this scheme. In steady state the FC and STATCOM each supply 75MVAr.

3. APPLICATION OF FIREFLY ALGORITHM FOR OBTAINING OPTIMAL GAIN VALUES FOR PI CONTROLLERS

In this paper, optimization of the rectifier and the inverter side DC power error is picked as a prime objective function which has to be minimized. To achieve the same DC power (P_{DCMEA}) and its reference (P_{DCREF}) is compared to get the error signal. The integral square error of the rectifier DC power error and inverter DC power error are controlled by the firefly algorithm [18], [19], [20], to fix the gain of the rectifier current PI controller and to fix the gain of the both inverter current PI controller and the gamma PI controller respectively. This approach guarantees the reduced computational procedure, faster recovery and reduced TOV. The schematic diagram of the firefly algorithm based tuning technique is shown in Figure 5. The general flow chart for minimization of the rectifier/ the inverter DC power error function using firefly algorithm is shown in Figure 6.

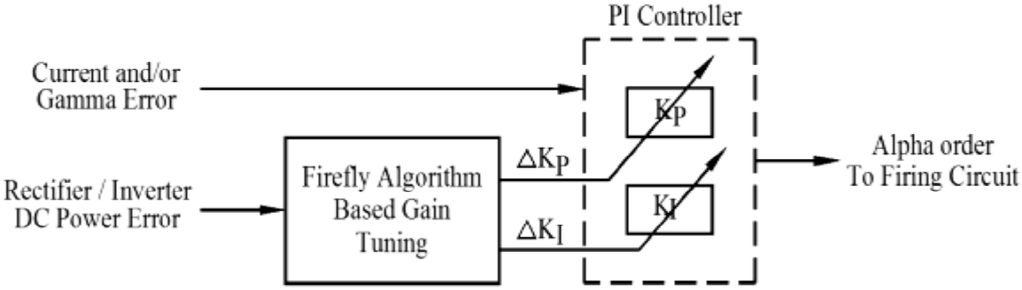

Figure 5: Schematic Diagram of the Firefly Algorithm Based Tuning Technique

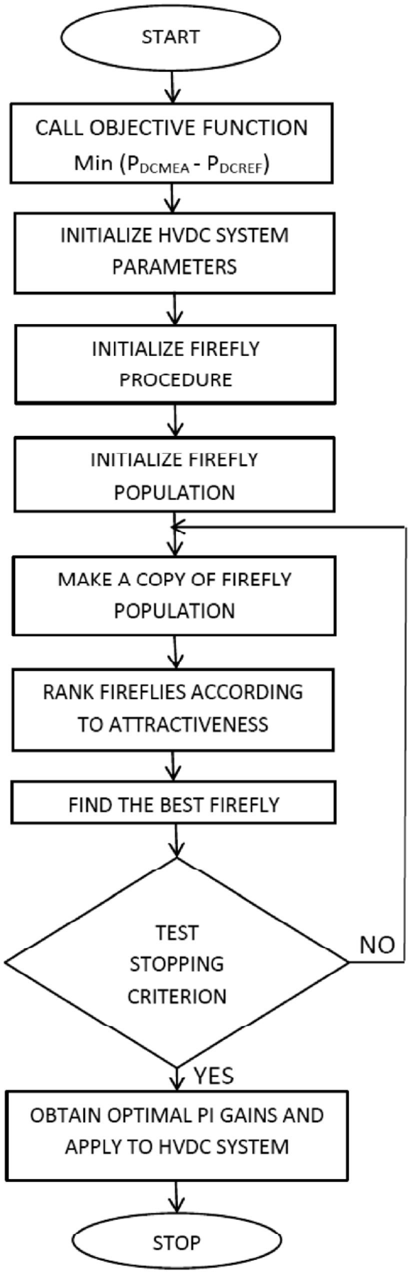

Figure 6: Flowchart for Minimization of the Rectifier/the Inverter DC Power Error Function using Firefly Algorithm

4. SIMULATION RESULTS AND DISCUSSION

In order to know the interaction between AC network and HVDC systems, simulation model is implemented in Matlab based on the data [21]. At the inverter AC Side, SC, SVC, STATCOM, FC+SC, FC+SVC and FC+STATCOM are the various RPC's considered for investigation. In all the cases steady state AC voltage and current waveforms at the inverter AC side and their harmonic spectrums are observed to study the quality of the AC supply. The transient performance of the HVDC system is analyzed in the presence of various RPC'S for a duration of two seconds under various fault conditions to study the suppression of TOV and fault recovery. For the purposes of comparison, identical fault duration of 0.05seconds was used for all types of faults. The inverter side RMS AC voltage waveforms are observed during various AC faults and DC fault on the rectifier side to study the TOV suppression capability of the proposed firefly algorithm based PI controller. In order to analyze the fault recovery capability with the proposed firefly algorithm based PI controller, the inverter DC power waveforms are observed, under various AC faults and DC faults at rectifier and inverter side. In all the cases, the TOV suppression and fault clearance capability of the firefly algorithm based PI controller are compared with conventional PI controller of an HVDC transmission system.

4.1. Inverter Side AC Harmonics

The inverter side AC voltage and current waveforms and their harmonic spectrums during steady state operation are presented in Figures 7, 8 and the results are listed in Table 1. From the inverter side AC waveforms and their harmonic spectrum, it is clear that in all the cases the voltage and current are equal to 1p.u and the harmonics are within tolerable limit. The 11th and 13th current harmonics are the foremost harmonics on the inverter AC side.

4.2. Temporary Overvoltage

When disturbances occur on the DC line or at the rectifier side, commonly temporary over voltage happens. It is usual practice a large number RLC based filters are provided in the inverter side of the HVDC system, in order to supply the part of necessary reactive power. During rectifier side AC or DC faults (the inverter side has no faults), the DC is blocked, and hence the reactive power of those filters will flow into the AC system, which often causes TOV. In order to suppress the TOV, the reactive power compensator and DC system PI controllers should respond quickly otherwise the TOV could be very high and could damage the insulation of the equipment. The ability of TOV suppression of various RPC's is demonstrated with the proposed firefly algorithm based PI controller and also compared to a conventional PI controller. From the inverter side RMS AC voltage waveforms presented in Figures 9, 10 and the results listed in Table 2, the existence of TOV with the presence of a conventional PI controller for various RPC's can be understood. The hybrid RPC's (FC+SC, FC+SVC and FC+STATCOM) has enhanced TOV controlling capability, than their individual performance (SC, SVC and STATCOM). In particular, FC+STATCOM have a smaller amount of TOV among the various RPC's. The TOV values further reduced due to the application firefly algorithm based PI controller compared to conventional PI controller.

4.3. Fault Recovery

The time taken by the HVDC system to recover the 80% of the pre-fault power after the fault clearance is known as DC power recovery time. The DC power recovery time is often desired the recovery ability of a DC system PI controller and the capability of the RPC's during system disturbances. From the inverter DC power recovery simulation results (Figures 11, 12 and Table 3), it is observed that in all the cases during rectifier side AC system faults, the system recovery with the firefly algorithm based PI controller is considerably faster than the conventional PI controller. On the other hand, for the faults in the rectifier DC side and inverter AC and DC side, the hybrid RPC's (FC+SC, FC+SVC and FC+STATCOM) has reduced fault clearing time than their individual performance (SC, SVC, and STATCOM). Specifically, the mixture of FC and STATCOM is taking much reduced time to clear the fault among the various RPC's. Further, the firefly algorithm based PI controller makes the system recovery much quicker than the conventional PI controller.

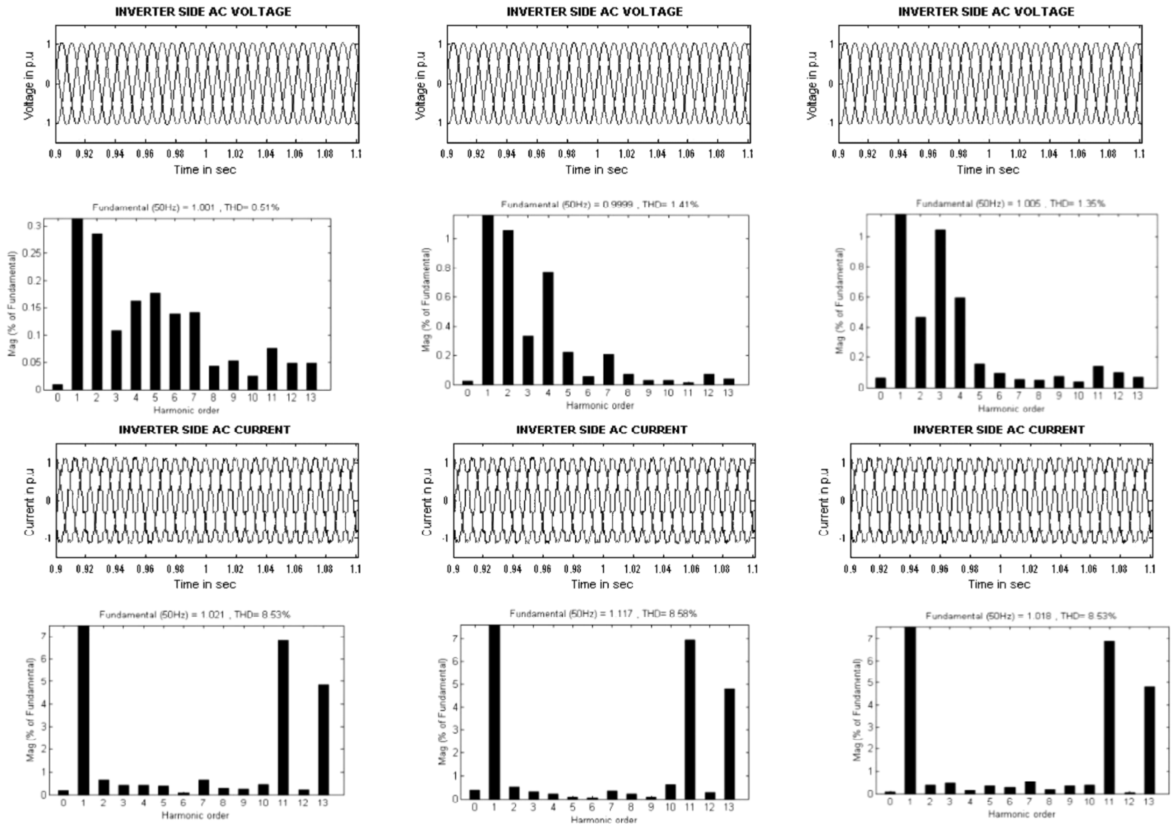

Figure 7: Inverter side AC Waveforms and their harmonic spectrums during steady state operation - with SC (left), - with SVC (middle) -with STATCOM (right)

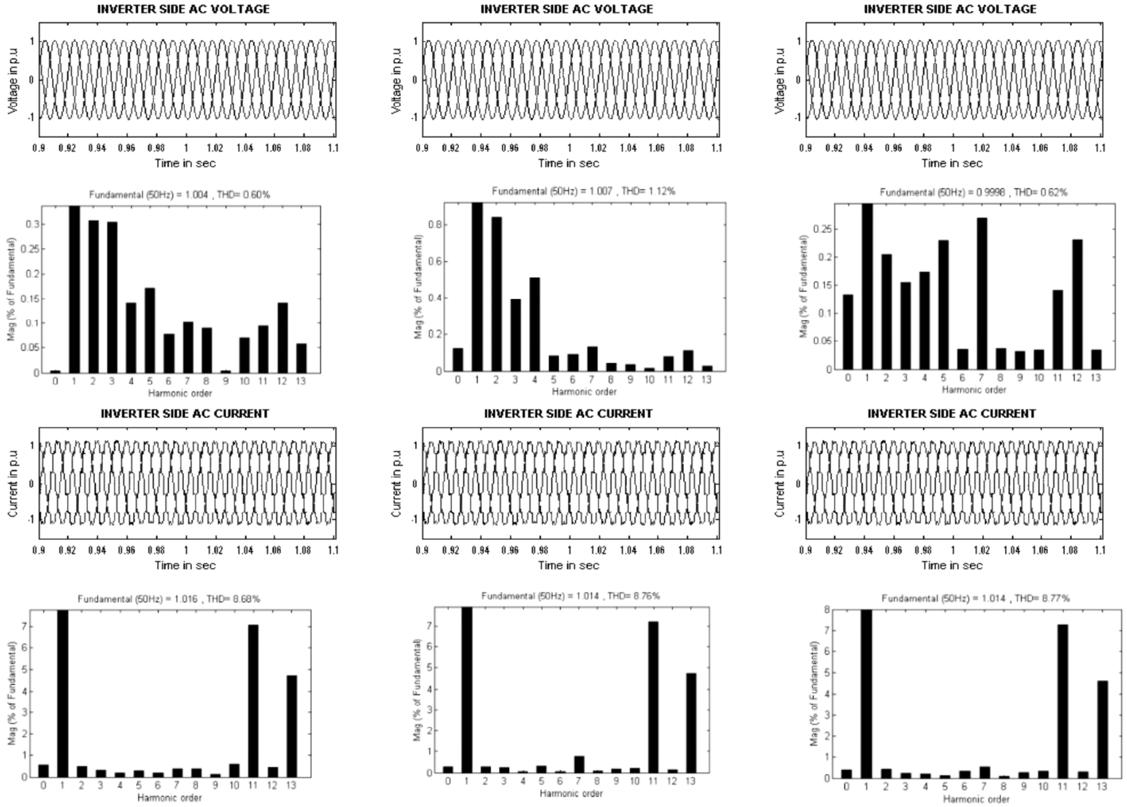

Figure 8: Inverter side AC waveforms and their harmonic spectrums during steady state operation with FC+SC (Left) - with FC+ SVC (Middle) -with FC+STATCOM (Right)

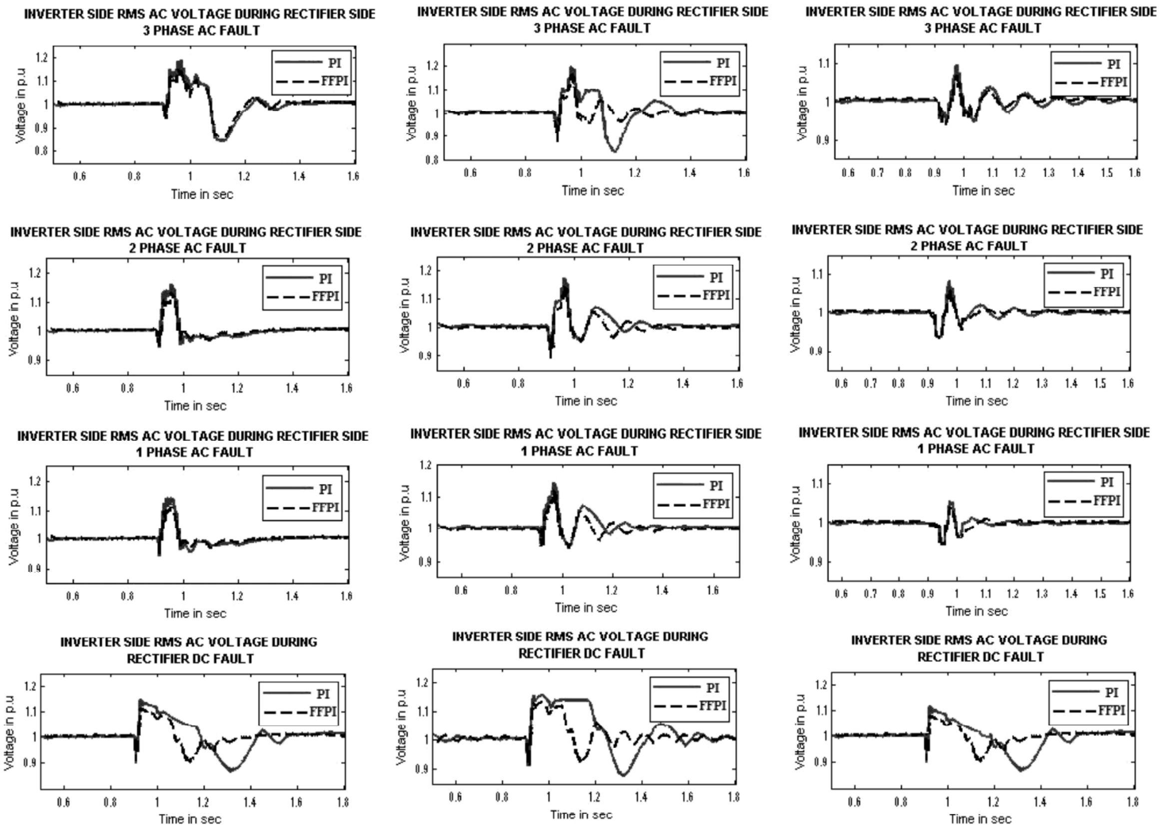

Figure 9: Inverter AC bus RMS voltage when disturbances occur on the DC line or at the rectifier side - with SC (left) - with SVC (middle) – with STATCOM (right)

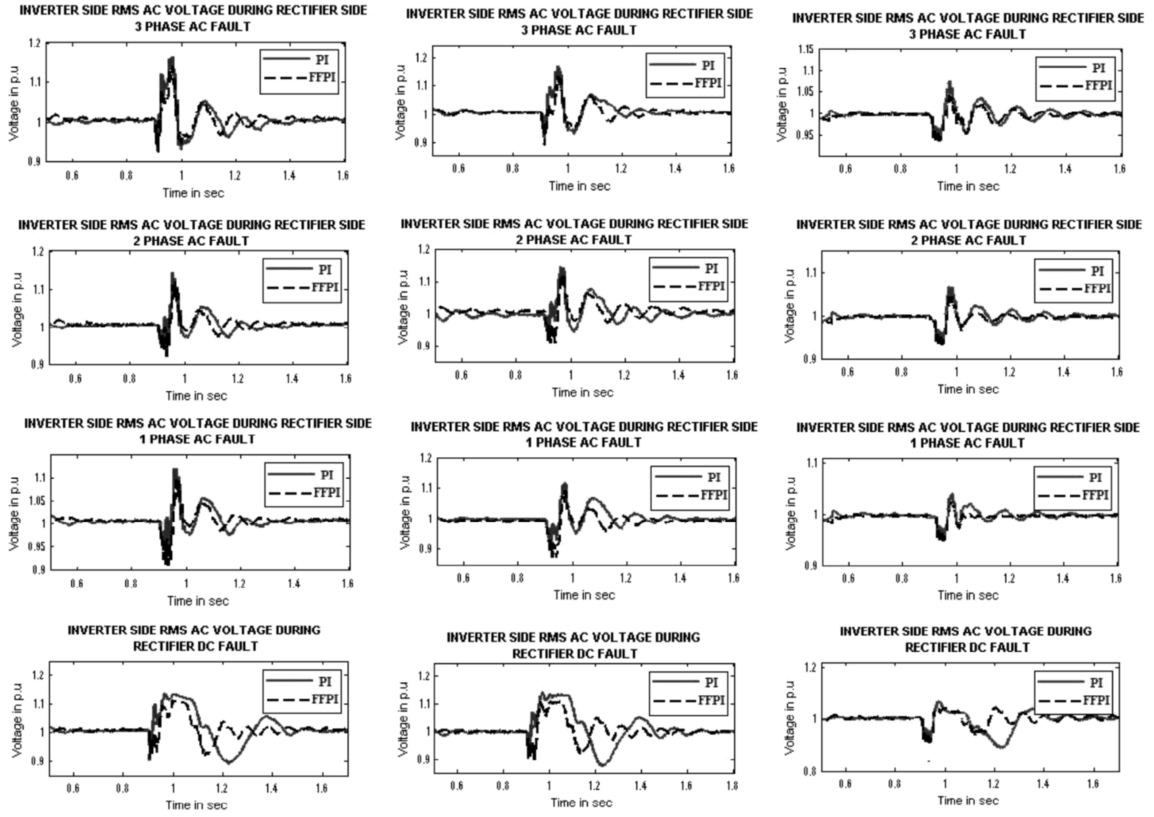

Figure 10: Inverter AC bus RMS voltage when disturbances occur on the DC line or at the rectifier side -with FC+SC (Left) - with FC+ SVC (Middle) -with FC+STATCOM (Right)

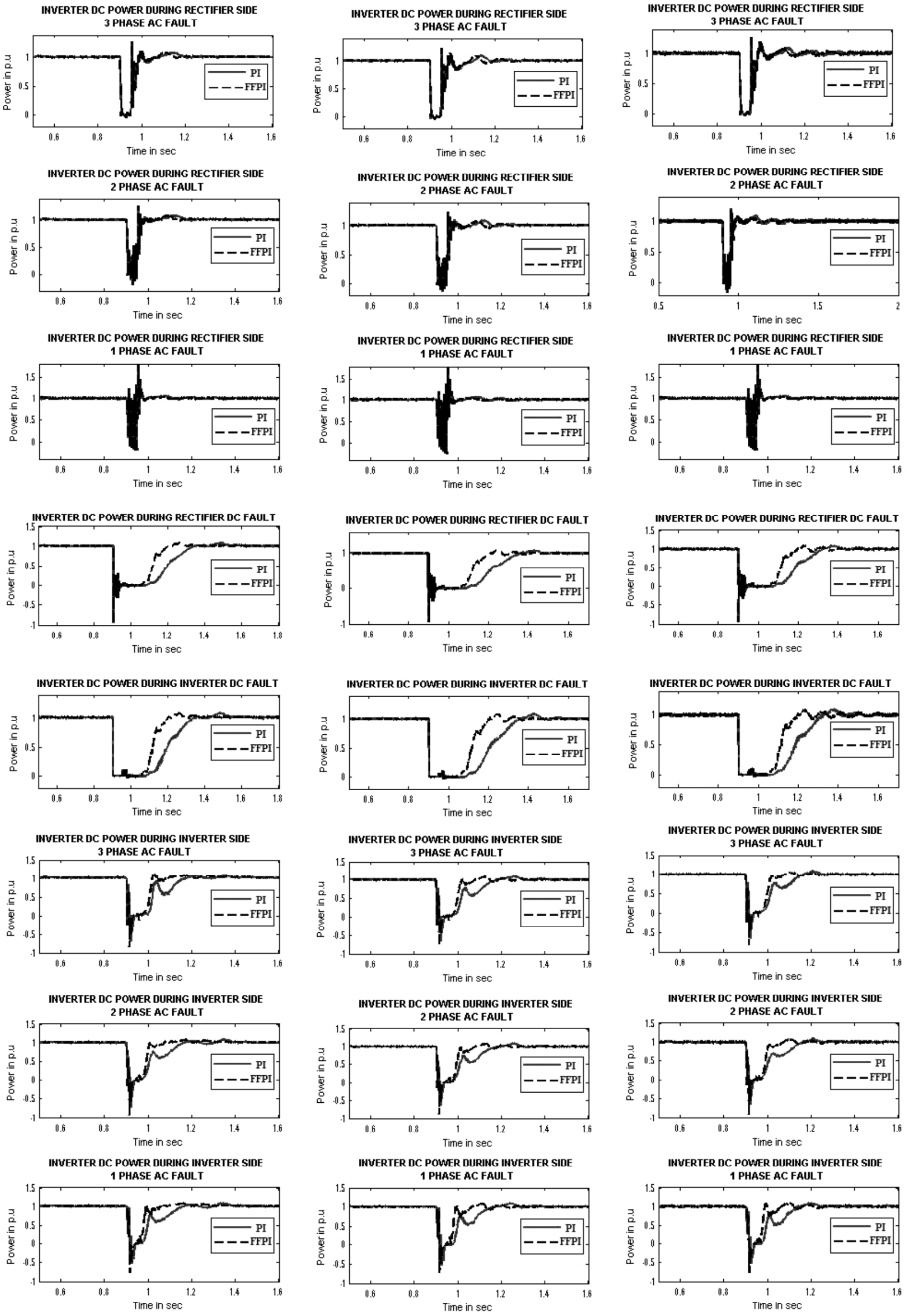

Figure 11: Inverter DC power when AC and DC disturbances occur on the rectifier side/ the inverter side -with SC (left) -with SVC (middle) – with STATCOM (right)

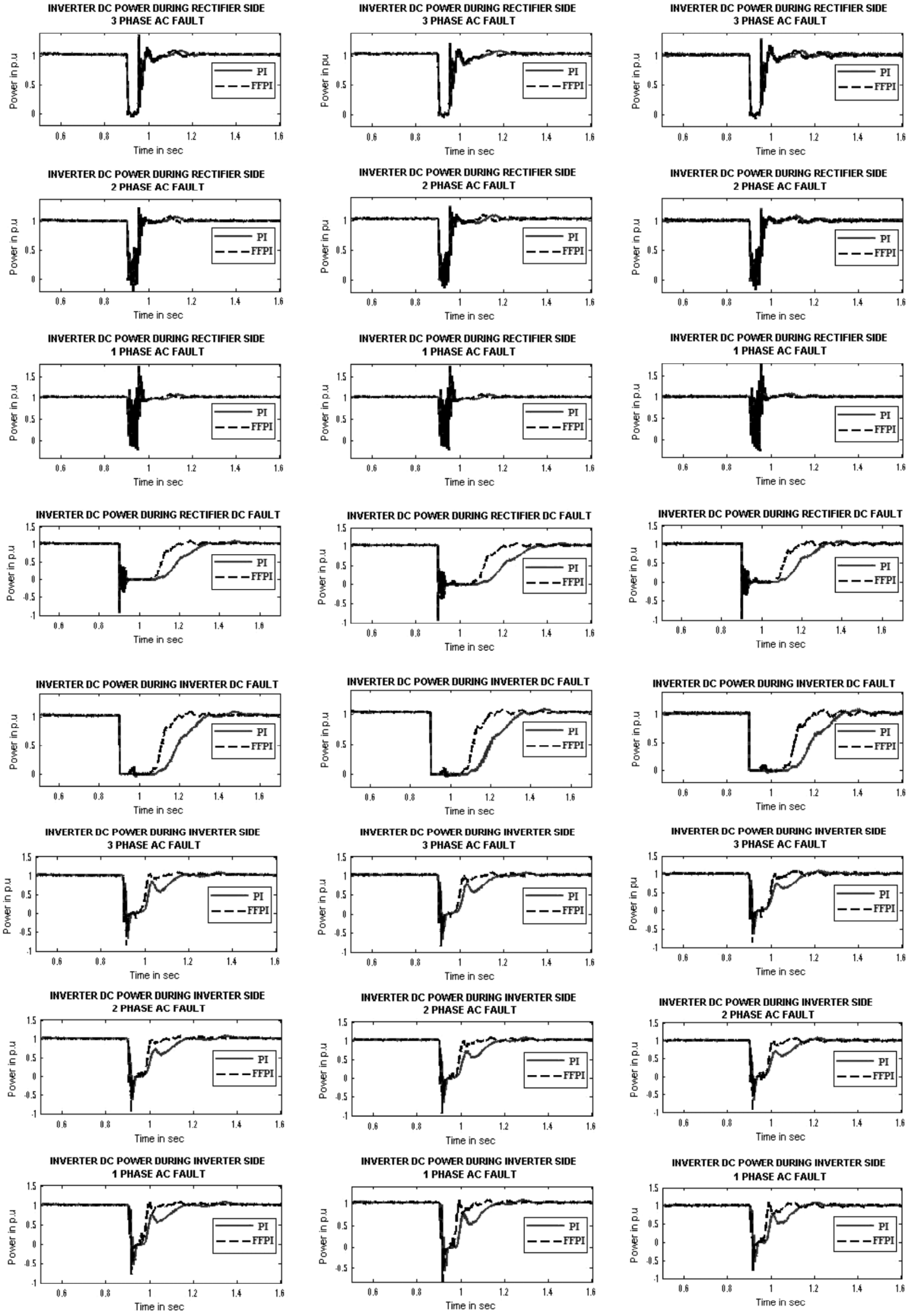
INVERTER DC POWER DURING RECTIFIER SIDE 3 PHASE AC FAULT

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Figure 12: Inverter DC power when AC and DC disturbances occur on the rectifier side /the inverter side -with FC+SC (Left) - with FC+ SVC (Middle) -with FC+STATCOM (Right)

Table 1
Harmonics Present in the Inverter Side AC Quantities

% AC Harmonics for various RPC's	*SC*	*SVC*	*STATCOM*	*FC+SC*	*FC+SVC*	*FC+ STATCOM*
Voltage	0.51	1.41	1.35	0.60	1.12	0.62
Current	8.53	8.58	8.53	8.68	8.76	8.77

Table 2
Over-voltage Level When Disturbances Occur on the DC Line or at the Rectifier Side during DC Block

TOV for Various RPC's in p.u		*Rectifier side 3Φ AC fault*	*Rectifier side 2Φ AC fault*	*Rectifier side 1Φ AC fault*	*Rectifier DC fault*
SC	**PI**	1.1821	1.1641	1.1451	1.1421
	FFPI	1.1583	1.1322	1.1147	1.1208
SVC	**PI**	1.1994	1.1740	1.1497	1.1558
	FFPI	1.1785	1.1466	1.1201	1.1311
STATCOM	**PI**	1.0962	1.0852	1.0641	1.0937
	FFPI	1.0693	1.0614	1.0411	1.0683
FC+SC	**PI**	1.1645	1.1433	1.1163	1.1360
	FFPI	1.1418	1.1134	1.0921	1.1102
FC+SVC	**PI**	1.1721	1.1486	1.1207	1.1426
	FFPI	1.1488	1.1221	1.0967	1.1147
FC+ STATCOM	**PI**	1.0732	1.0690	1.0479	1.0691
	FFPI	1.0483	1.0456	1.0263	1.0472

Table 3
Inverter DC Power When AC and DC Disturbances Occur on the Rectifier and the Inverter Side

DC power recovery time for Various RPC's in seconds		*Rectifier side 3Φ AC fault*	*Rectifier side 2Φ AC fault*	*Rectifier side 1Φ AC fault*	*Rectifier DC fault*	*Inverter DC fault*	*Inverter side 3Φ AC fault*	*Inverter side 2Φ AC fault*	*Inverter side 1Φ AC fault*
SC	**PI**	0.034	0.022	0.013	0.364	0.365	0.169	0.163	0.151
	FFPI	0.032	0.021	0.012	0.243	0.242	0.058	0.053	0.049
SVC	**PI**	0.035	0.023	0.014	0.382	0.384	0.173	0.165	0.156
	FFPI	0.033	0.022	0.013	0.253	0.254	0.065	0.060	0.055
STATCOM	**PI**	0.032	0.021	0.012	0.350	0.353	0.163	0.159	0.147
	FFPI	0.030	0.020	0.011	0.230	0.231	0.051	0.047	0.043
FC+SC	**PI**	0.032	0.021	0.012	0.354	0.357	0.165	0.158	0.146
	FFPI	0.030	0.020	0.011	0.239	0.241	0.054	0.049	0.044
FC+SVC	**PI**	0.033	0.022	0.013	0.376	0.377	0.168	0.161	0.153
	FFPI	0.031	0.021	0.011	0.248	0.250	0.063	0.058	0.053
FC+ STATCOM	**PI**	0.030	0.020	0.011	0.337	0.339	0.159	0.154	0.143
	FFPI	0.028	0.019	0.010	0.219	0.221	0.047	0.041	0.037

5. CONCLUSION

In this paper, an in depth performance analysis of firefly algorithm based optimal PI controller for the rectifier and the inverter control in a monopolar HVDC system feeding a weak AC network was carried out with various hybrid RPC's at inverter AC side. The hybrid RPC's considered were FC+SC, FC+SVC and

FC+STATCOM. This involvement can be very useful for designing and safeguarding persons, for analyzing the interaction between AC networks and HVDC systems under different operating environment. The HVDC transmission system model was implemented in the Matlab environment. The transient performances of the hybrid RPC's in an HVDC system were compared with SC, SVC, STATCOM, under various fault condition to study the suppression of TOV and fault recovery. The simulation results, certify that the equal mingling of FC+STATCOM has the stable and faster response and display the superiority of firefly algorithm based PI controller over the conventional fixed gain PI controller. The harmonic study outcome also assures the quality of power supply on inverter AC side.

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