International Journal of Inventive Engineering and Sciences (IJIES)
ISSN: 2319–9598, Volume-3 Issue-8, July 2015

Transient Performance of a Multi-Terminal HVDC Transmission System Feeding Very Weak AC Networks

S. Seenivasan, S. Singaravelu

Abstract*— *This paper analyses transient performances of a line commutated converter (LCC)-multi-terminal HVDC transmission system (MTDC) feeding very weak AC networks with firefly algorithm based optimal proportional-integral (PI) controller for rectifiers and inverters control and hybrid reactive power compensators (RPC's) at inverters AC side. The hybrid compensator is attained by equally mixing the fixed capacitor (FC) with any one of the following compensators: synchronous compensator (SC); static var compensator (SVC); static synchronous compensator (STATCOM). The MTDC transmission system model is simulated using Matlab. The transient performances of hybrid RPC's (FC+SC, FC+SVC and FC+STATCOM) are investigated during various fault conditions 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 authorize that the equal combination 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. The harmonic existing in the inverter AC side is also observed under steady state operation to assure the quality of power supply.

Index Terms*—*Firefly algorithm, Hybrid RPC, MTDC, PI controller, Very weak AC system.

I. INTRODUCTION

The MTDC power transmission technology has a) rapid rises in the power carrying capacity, b) flexibility in power control and c) the possibility of connecting new offshore load/generation terminal [1-3]. During occurrence of the fault, in the MTDC system without appropriate control and protection, the fault at one terminal will affect the inter-connected terminals. Under such circumstances of the MTDC system, by presuming that the blocking of the converter is successful, special control and protection is offered. On the other hand, this presumption is not necessarily valid in terms of the practical operation of converters in the HVDC system [4] such as 1) During the communication outage of control signals, the whole converter can be out of control and cannot be blocked, 2) A more common condition is that one of the six pulse converter arm is failed to be blocked [5], [6]. Hence, it is worth identifying the possible hazard to the MTDC system by propagating the fault at one terminal without blocking the converters.

Further, 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 enriches the stability of the entire power grid. The significance of this interaction [7] largely depends on the strength of the AC system at the converter bus, which is presented by the short circuit ratio (SCR). The following SCR values [8] can be used to classify AC systems: a) SCR >3 for a strong system, b) $2 \leq$ SCR < 3 for a weak system, c) SCR < 2 for a very weak system. Several works have been accomplished to identify the interaction between very weak AC networks and HVDC systems. The performance of the monopolar HVDC system under AC and DC disturbances [9] is analysed with dynamic voltage control devices at the inverters of very weak AC systems by considering the compensators: FC, SC, SVC and a mix of the SC and SVC. The feasibility to interconnect AC/DC systems, leading to very weak SCR's lower than 1.5 [10] is exposed with STATCOM for reactive power compensation. A multilevel gate turn-off (GTO) thyristor inverter as an advanced static var compensator [11] is proposed for the monopolar HVDC system and the suppression of temporary over voltage (TOV) and DC power recovery performance of the advanced static var compensator investigated at an HVDC converter terminal, with a very low SCR AC system and the simulation results are compared under various AC and DC disturbances with the reactive power compensation options available. To make the analysis complete, it is highly necessary to consider the suppression of TOV and fault recovery performances of monopolar HVDC system feeding a very weak AC network with the following hybrid RPC's as well, FC+SC, FC+SVC and FC+STATCOM. Therefore, in [12] transient performance has been carried out for an HVDC transmission system connected to very weak AC network with the following RPC's: SC, SVC, STATCOM, FC+SC, FC+SVC and FC+STATCOM. As an addition, in this paper, the detailed simulation study carried out in the monopolar HVDC system is extended to an MTDC system by analyzing the DC power recovery performance and suppression of TOV during various transient fault conditions. The harmonics investigation is also done under steady state to insure the quality of power supply on inverter AC side.

Revised Version Manuscript Received on July 08, 2015.

S. Seenivasan, Department of Electrical Engineering, Annamalai University, Annamalainagar-608002, Tamil Nadu, India.

S. Singaravelu, Department of Electrical Engineering, Annamalai University, Annamalainagar-608002, Tamil Nadu, India.

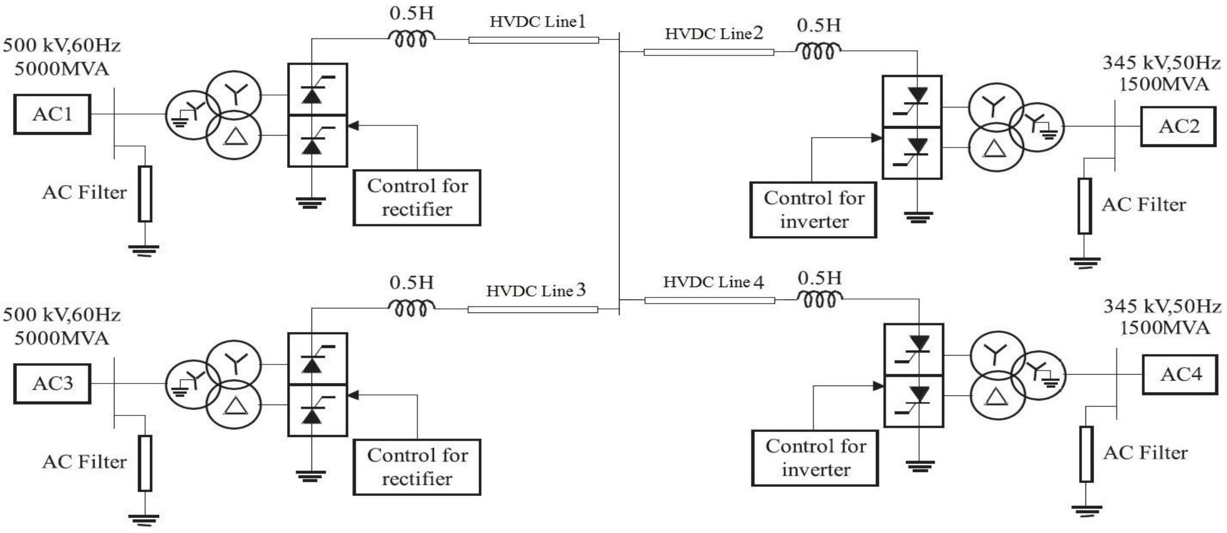
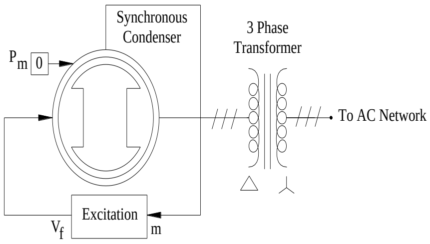


Fig. 1: Four-Terminal HVDC transmission system model feeding very weak AC networks.

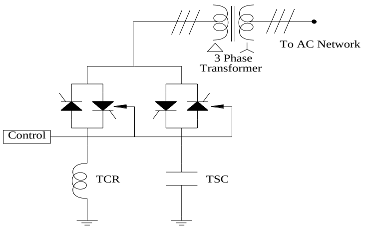
The conventional PI controller used for rectifier and inverter controllers of HVDC system causes instability due to deficiency in tuning its gain during abnormal conditions. To overcome this drawback intelligent technique [13-16], are introduced for proper tuning of the PI controller parameters. However, 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. 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 firefly algorithm based optimal PI controller, on transient performance, it has been compared with conventional PI controller.

II. MODELLING OF MTDC TRANSMISSION SYSTEM

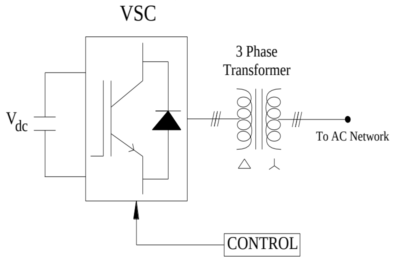
A line commutated converter based four-terminal HVDC system feeding two strong AC networks [17], in which inverter side AC networks are replaced by very weak AC networks as shown in the Fig. 1. Each rectifier side AC system of 500kV, 5000MVA, 60Hz is connected to each inverter side AC system of 345kV, 1500MVA, 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 harmonics and synchronous or static compensator or fixed capacitor with synchronous or static compensator is used (150MVAr) for reactive power compensation. Each rectifier and inverter is 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. Each rectifier is equipped with a current controller to maintain the DC system current constant. Each 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 each rectifier and each inverter DC protection functions are implemented in each converter. In the inverter side AC network, the following six reactive power compensator options is studied.



(a) SC



(b) SVC



(c) STATCOM

Fig. 2: Schematic of RPC's.

A. Synchronous Compensator

The SC model of 150MVAr shown in Fig. 2 (a) 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.

B. Static Var Compensator

A 150MVAr SVC is shown in Fig. 2 (b) 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 60MVAr inductive.

C. Static Synchronous Compensator

The STATCOM shown in Fig. 2 (c) 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.

D. 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.

E. 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.

F. 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.

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

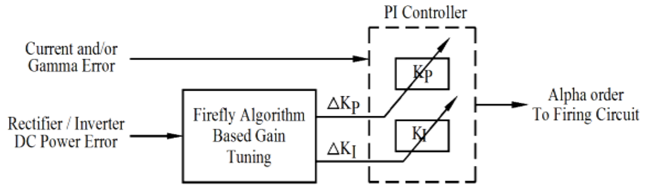


Fig. 3: Schematic Diagram of the Firefly Algorithm Based Tuning Technique.

In this paper, an 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 ($_{PDCREF}$) 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 [18-21], 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 Fig 3. The general flow chart for minimization of the rectifier/ the inverter DC power error function using firefly algorithm is shown in Fig. 4.

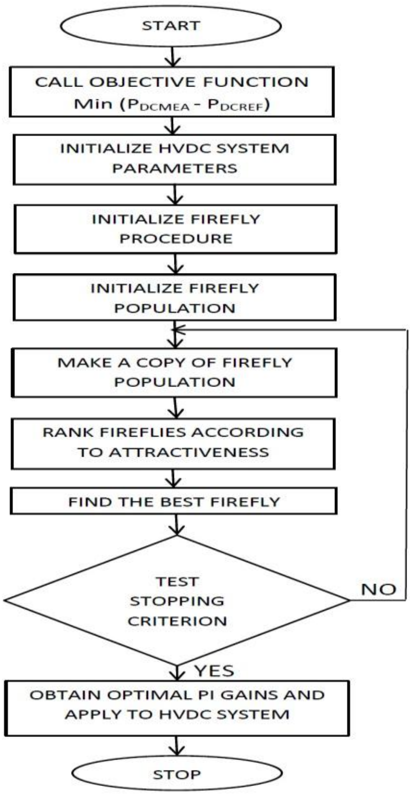


Fig. 4: Flowchart for minimization of the rectifier/the inverter DC power error function using firefly algorithm.

IV. SIMULATION RESULTS AND DISCUSSION

In order to know the interaction between very weak AC networks and HVDC systems, the simulation model is implemented in Matlab based on the data [22]. At the inverters 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. During the transient performance analysis, faults are considered only in rectifier station 1 and inverter station 1 and their impact on inverter station 1 and 2 is presented (Since the rectifier 1 and 2 and inverter 1 and 2 are identical in the system under study).

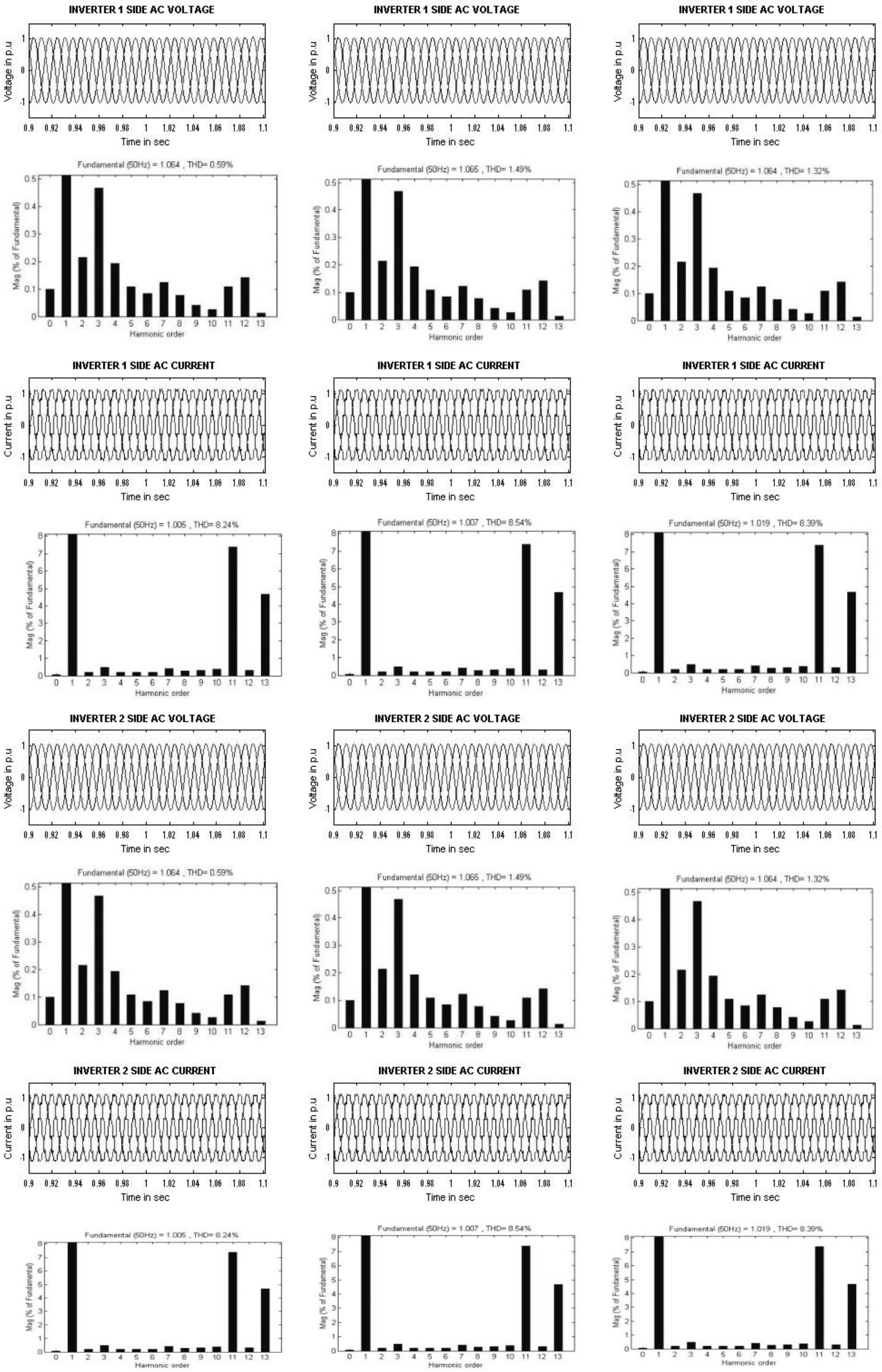


Fig. 5: Inverter 1 and 2 side AC waveforms and their harmonic spectrums during steady state operation -with SC (Left), -with SVC (Middle), -with STATCOM (Right).

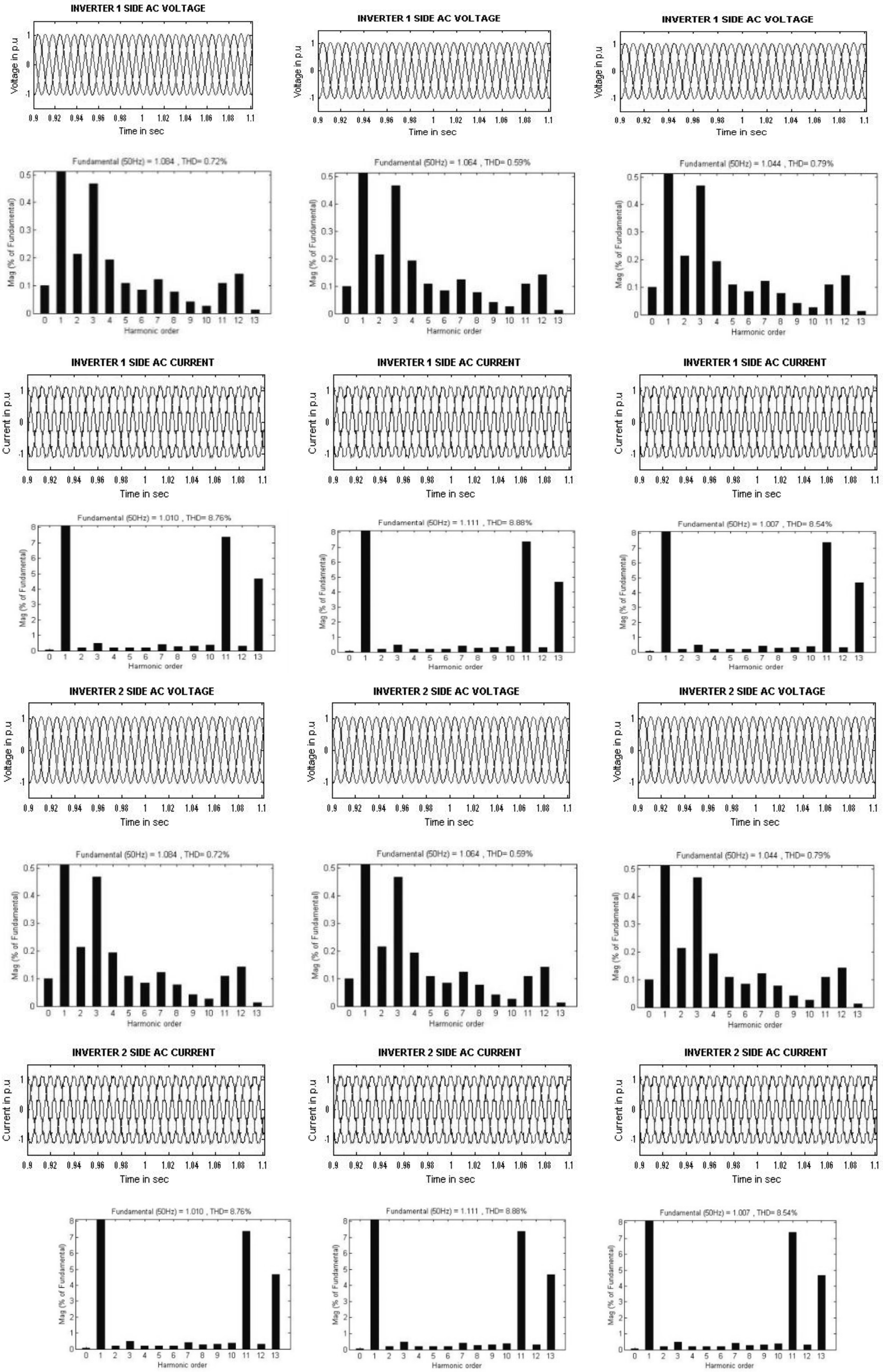
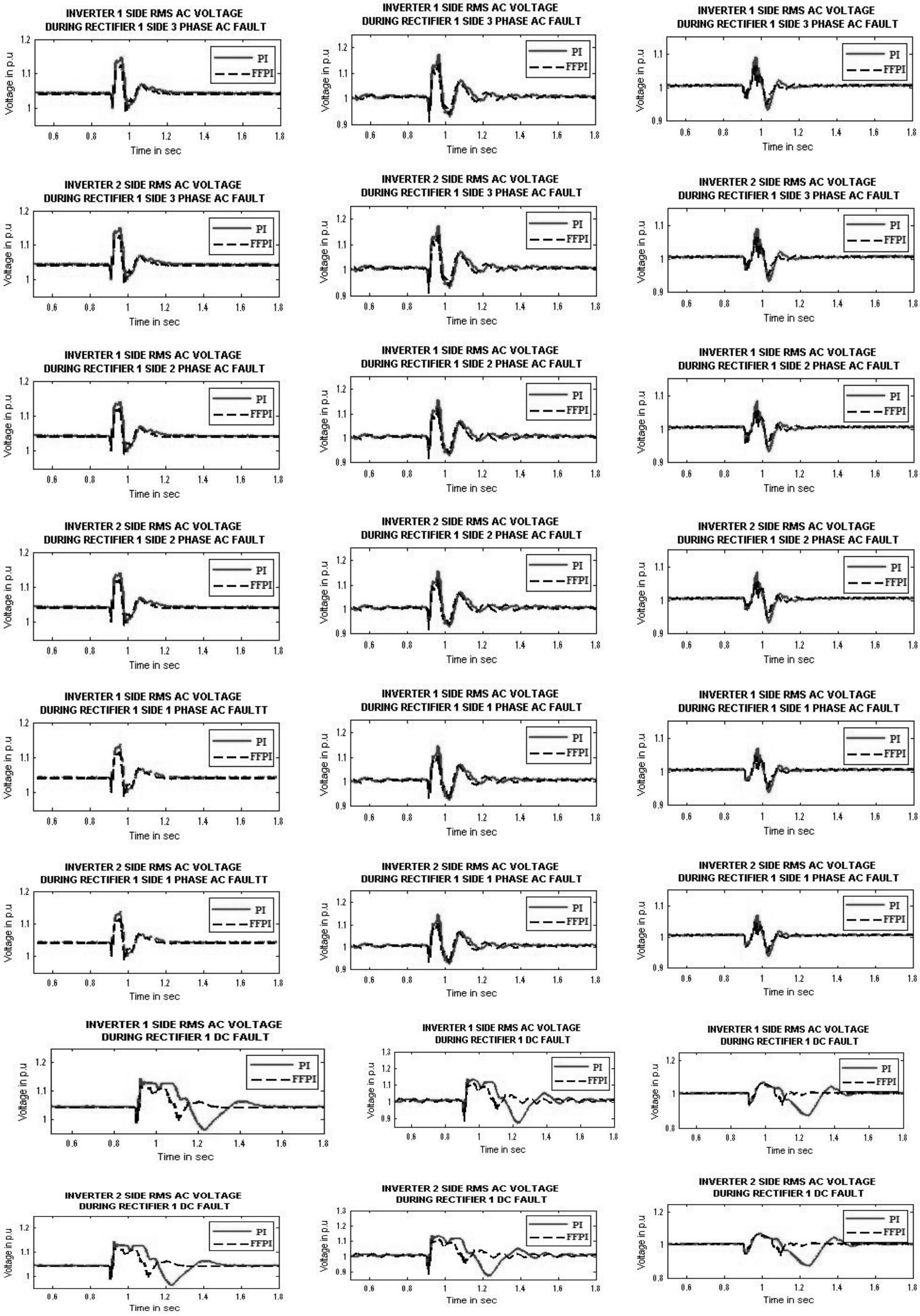


Fig. 6: Inverter 1 and 2 side AC waveforms and their harmonic spectrums during steady state operation -with FC+SC (Left), -with FC+SVC (Middle), -with FC+ STATCOM (Right).



INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 1 PHASE AC FAULTT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 1 PHASE AC FAULTT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 DC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 DC FAULT

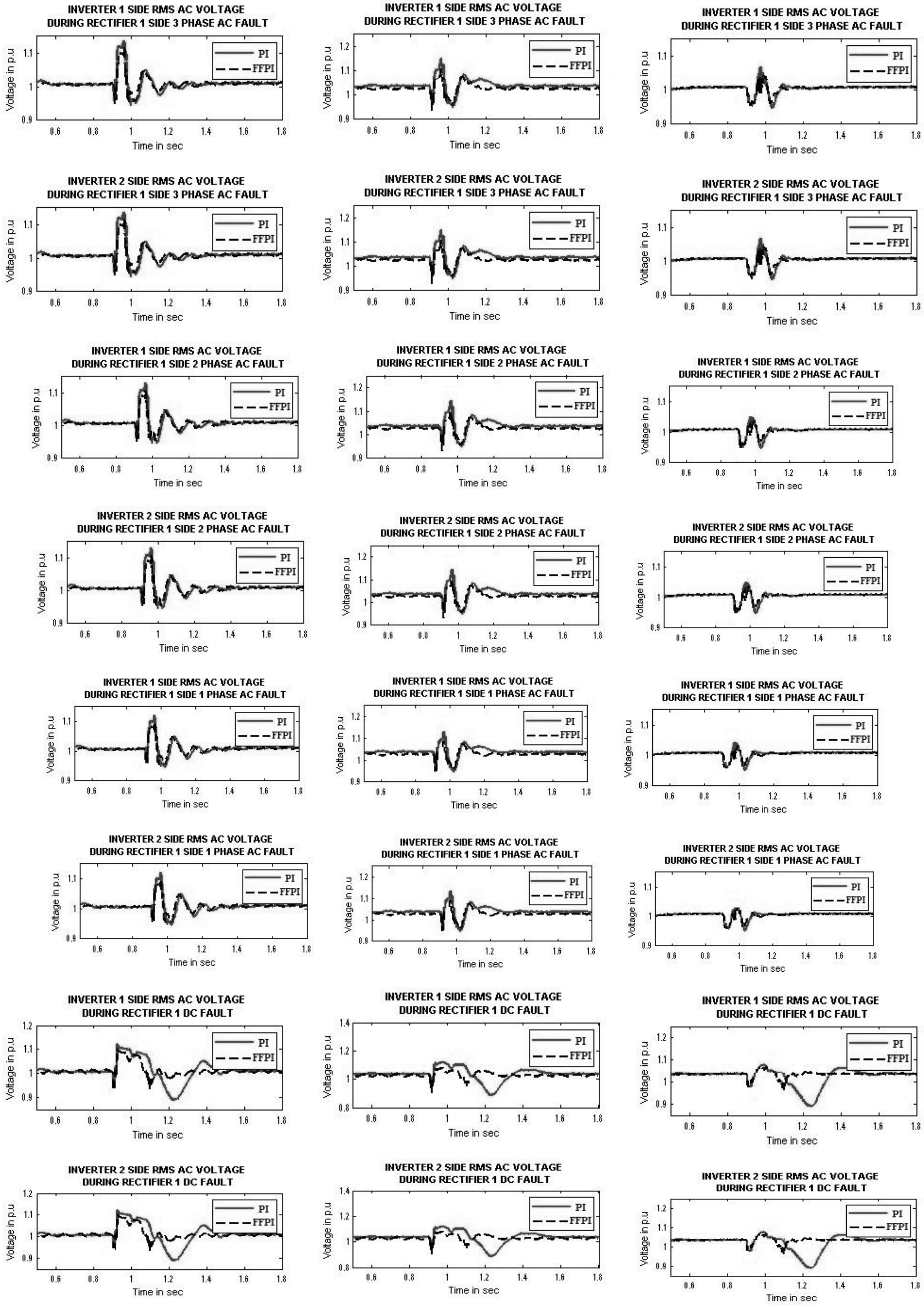
INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 DC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 DC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 DC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 DC FAULT

Fig. 7: Inverter 1 and 2 AC bus RMS voltage when disturbances occur on the DC line or at the rectifier 1 AC side -with SC (Left), -with SVC (Middle), -with STATCOM (Right).


INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

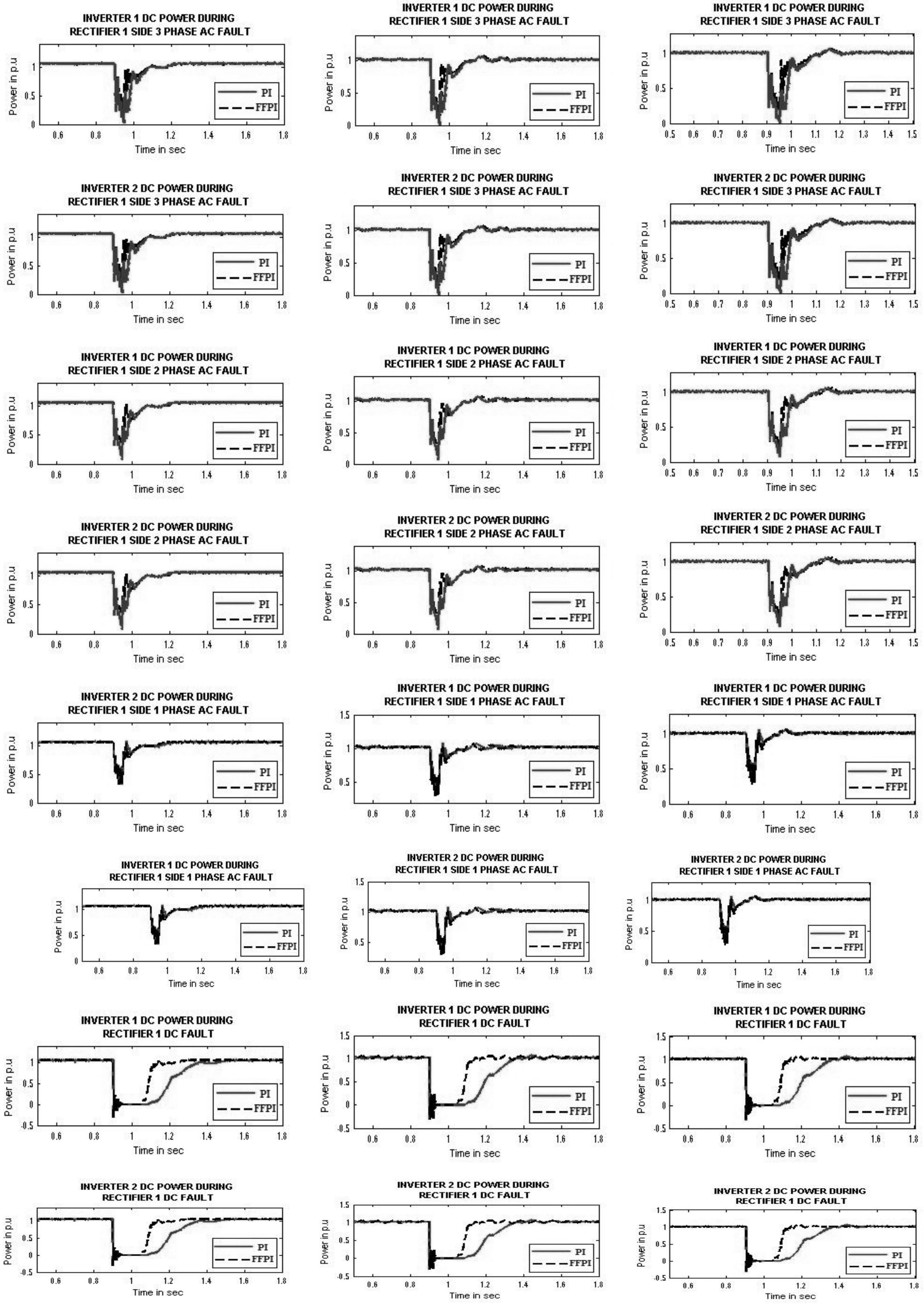
INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 1 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 DC FAULT

INVERTER 2 SIDE RMS AC VOLTAGE DURING RECTIFIER 1 DC FAULT

Fig. 8: Inverter 1 and 2 AC bus RMS voltage when disturbances occur on the DC line or at the rectifier 1 AC side -with FC+SC (Left), -with FC+SVC (Middle), -with FC+STATCOM (Right).



INVERTER 1 DC POWER DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 SIDE 3 PHASE AC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 SIDE 2 PHASE AC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 SIDE 1 PHASE AC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 DC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 DC FAULT

INVERTER 1 DC POWER DURING RECTIFIER 1 DC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 DC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 DC FAULT

INVERTER 2 DC POWER DURING RECTIFIER 1 DC FAULT

Fig. 9: Inverter 1 and 2 DC power when AC and DC disturbances occur on the rectifier 1 side -with SC (Left), -with SVC (Middle), -with STATCOM (Right).

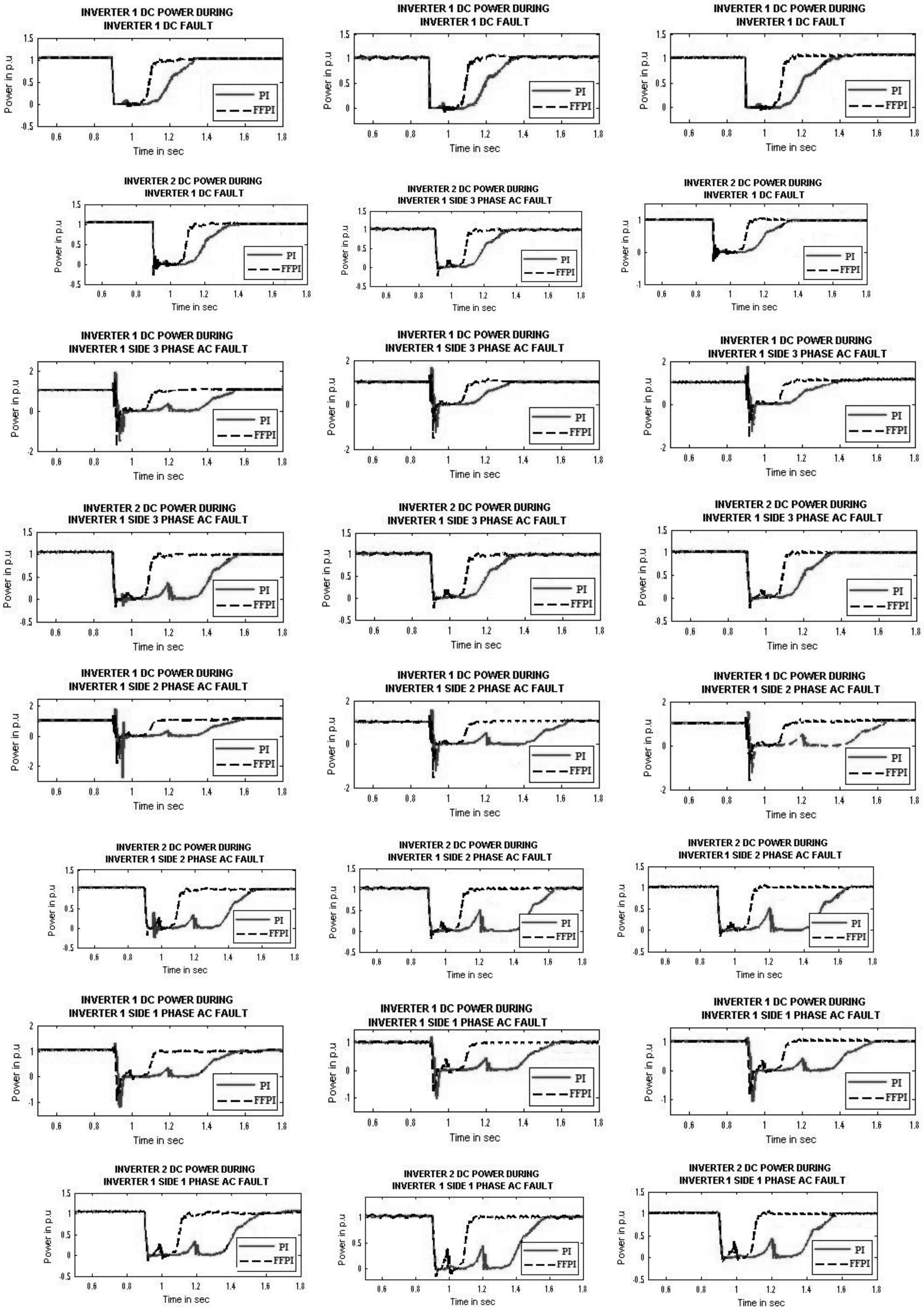


Fig. 10: Inverter 1 and 2 DC power when AC and DC disturbances occur on the inverter 1 side -with SC (Left), -with SVC (Middle), -with STATCOM (Right).

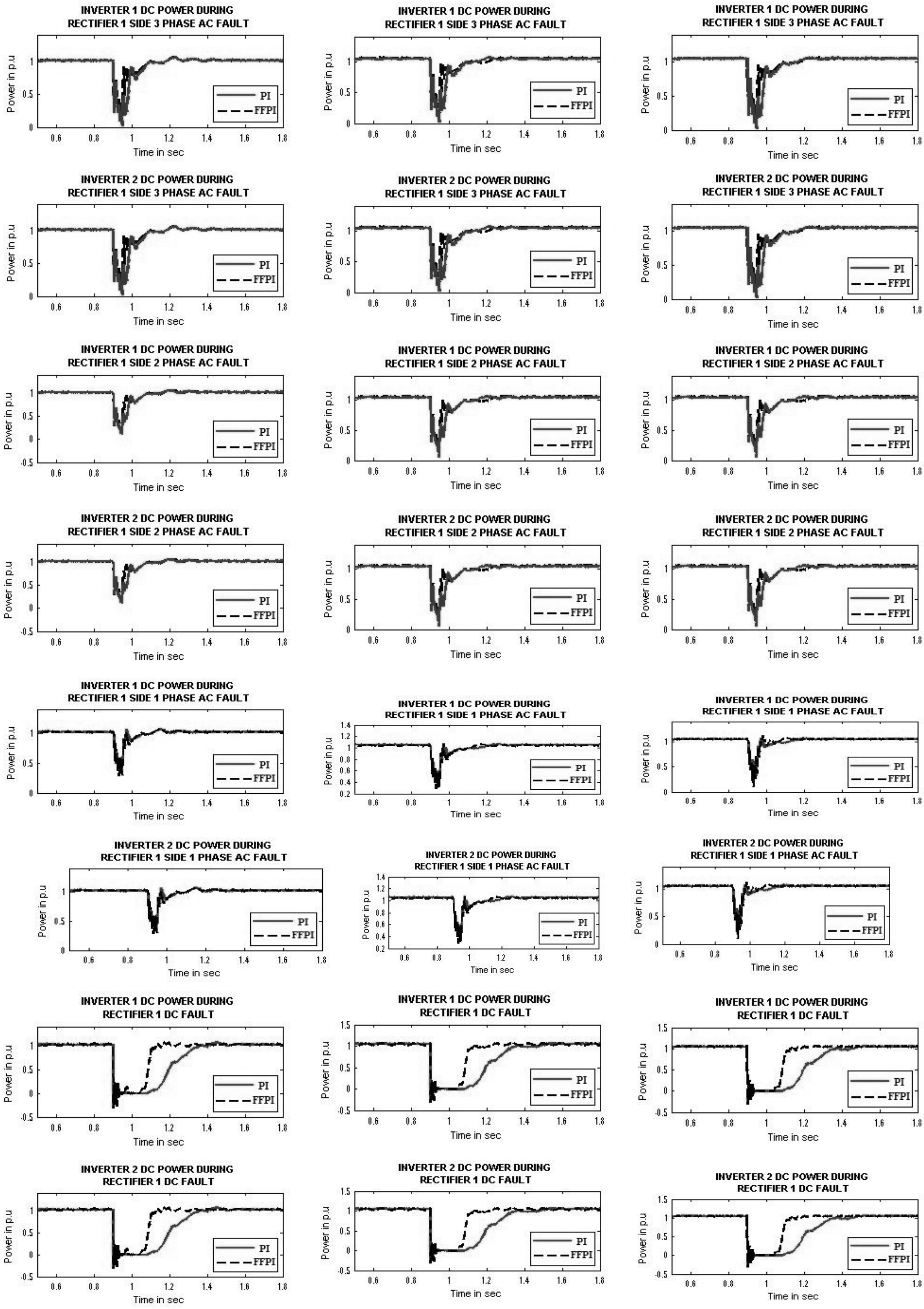


Fig. 11: Inverter 1 and 2 DC power when AC and DC disturbances occur on the rectifier 1 side -with FC+SC (Left), -with FC+SVC (Middle), -with FC+STATCOM (Right).

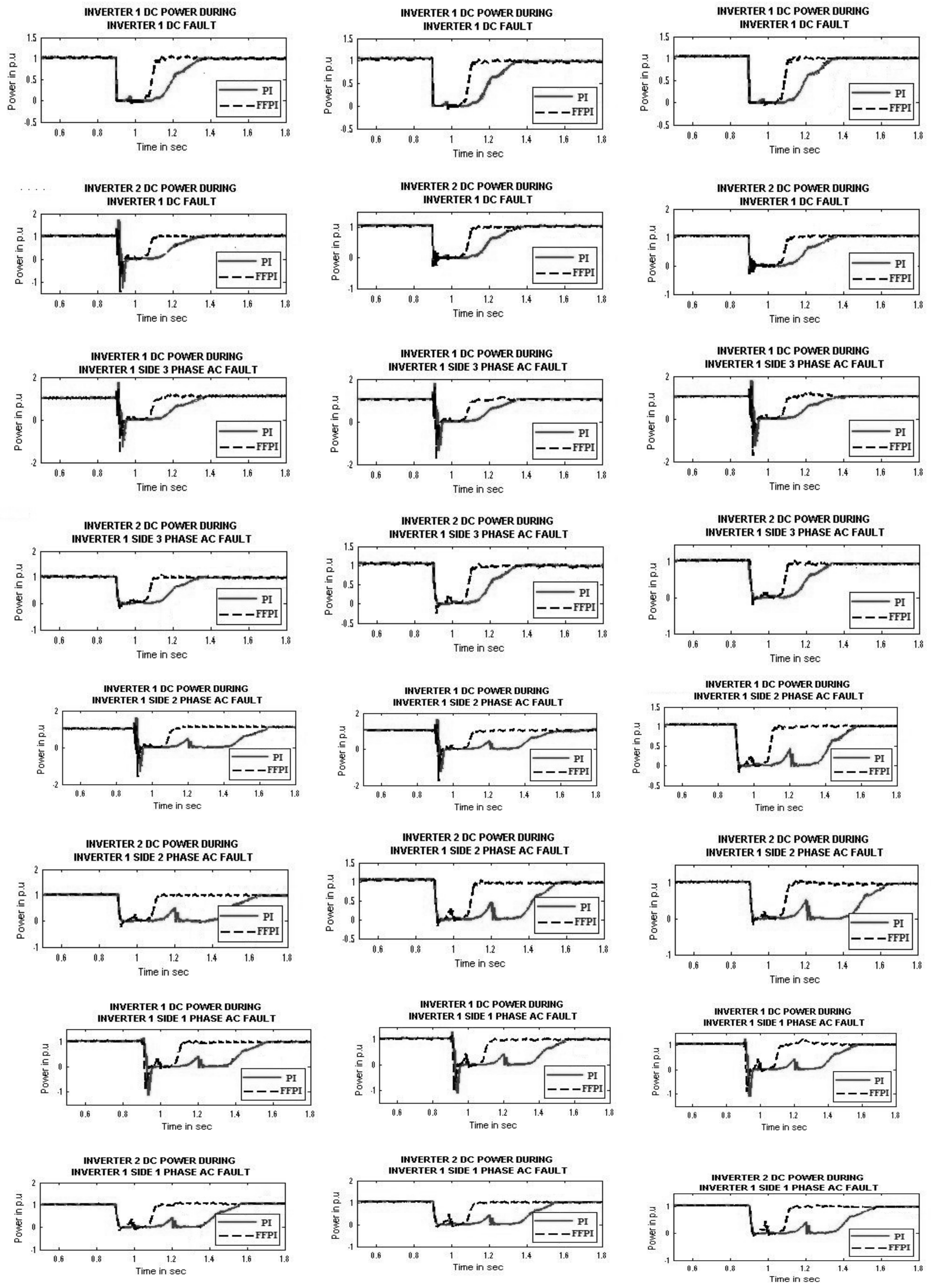


Fig. 12: Inverter1 and 2 DC power when AC and DC disturbances occur on the inverter 1 side
-with FC+SC (Left), -with FC+SVC (Middle), -with FC+STATCOM (Right).

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.

A. Inverter Side AC Harmonics

The inverter side AC voltage and current waveforms and their harmonic spectrums during steady state operation are presented in Fig. 5, 6 and the results are listed in Table I. 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.

B. 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 Fig. 7, 8 and the results listed in Table II, the existence of TOV in 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 . 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 base PI controller.

C. 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 (Fig. 9, 10, 11, 12 and Table III, IV) 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.

Table I: Harmonics present in the inverter side AC quantities.

% AC Harmonics for various RPC's		**SC**	**SVC**	**STATCOM**	**FC+SC**	**FC+SVC**	**FC+STATCOM**
Voltage	**Inverter 1**	0.59	1.49	1.32	0.72	0.59	0.79
	Inverter 2	0.59	1.49	1.32	0.72	0.59	0.79
Current	**Inverter 1**	8.24	8.54	8.39	8.76	8.88	8.54
	Inverter 2	8.24	8.54	8.39	8.76	8.88	8.54

Table II: Over-voltage level when disturbances occur on the DC line or at the rectifier 1 side during DC block .

TOV for various RPC's in p.u		**Rectifier 1 side 3Φ AC fault**		**Rectifier 1 side 2Φ AC fault**		**Rectifier 1 side 1Φ AC fault**		**Rectifier 1 DC fault**	
		Inverter 1	**Inverter 2**	**Inverter 1**	**Inverter 2**	**Inverter 1**	**Inverter 2**	**Inverter 1**	**Inverter 2**
SC	**PI**	1.1844	1.1844	1.1675	1.1675	1.1462	1.1462	1.1421	1.1421
	FFPI	1.1565	1.1565	1.1382	1.1382	1.1164	1.1164	1.1208	1.1208
SVC	**PI**	1.1956	1.1956	1.1795	1.1795	1.1501	1.1501	1.1558	1.1558
	FFPI	1.1724	1.1724	1.1511	1.1511	1.1225	1.1225	1.1311	1.1311
STATCOM	**PI**	1.0932	1.0932	1.0885	1.0885	1.0665	1.0665	1.0937	1.0937
	FFPI	1.0624	1.0624	1.0634	1.0634	1.0398	1.0398	1.0683	1.0683
FC+SC	**PI**	1.1675	1.1675	1.1453	1.1453	1.1186	1.1186	1.1360	1.1360
	FFPI	1.1441	1.1441	1.1162	1.1162	1.0955	1.0955	1.1102	1.1102
FC+SVC	**PI**	1.1785	1.1785	1.1548	1.1548	1.1257	1.1257	1.1426	1.1426
	FFPI	1.1479	1.1479	1.1260	1.1260	1.0967	1.0967	1.1147	1.1147
FC+ STATCOM	**PI**	1.0776	1.0776	1.0664	1.0664	1.0479	1.0479	1.0691	1.0691
	FFPI	1.0469	1.0469	1.0421	1.0421	1.0263	1.0263	1.0472	1.0472

Table III: Inverter 1 and 2 DC power when AC and DC disturbances occur on the rectifier 1side

DC power recovery time for Various RPC's in seconds		Rectifier 1 side 3Φ AC fault		Rectifier 1 side 2Φ AC fault		Rectifier 1 side 1Φ AC fault		Rectifier 1DC fault	
		Inverter 1	Inverter 2	Inverter 1	Inverter 2	Inverter 1	Inverter 2	Inverter 1	Inverter 2
SC	**PI**	0.090	0.090	0.079	0.079	0.053	0.053	0.399	0.399
	FFPI	0.044	0.044	0.037	0.037	0.022	0.022	0.189	0.189
SVC	**PI**	0.099	0.099	0.085	0.085	0.060	0.060	0.412	0.412
	FFPI	0.049	0.049	0.042	0.042	0.027	0.027	0.195	0.195
STATCOM	**PI**	0.084	0.084	0.075	0.075	0.048	0.048	0.384	0.384
	FFPI	0.039	0.039	0.032	0.032	0.019	0.019	0.178	0.178
FC+SC	**PI**	0.087	0.087	0.077	0.077	0.047	0.047	0.388	0.388
	FFPI	0.041	0.041	0.035	0.035	0.018	0.018	0.182	0.182
FC+SVC	**PI**	0.095	0.095	0.082	0.082	0.055	0.055	0.397	0.397
	FFPI	0.045	0.045	0.040	0.040	0.024	0.024	0.187	0.187
FC+ STATCOM	**PI**	0.079	0.079	0.071	0.071	0.043	0.043	0.376	0.376
	FFPI	0.034	0.034	0.028	0.028	0.016	0.016	0.169	0.169

Table IV: Inverter 1 and 2 DC power when AC and DC disturbances occur on the inverter 1 side

DC power recovery time for Various RPC's in seconds		Inverter 1 DC fault		Inverter 1 side 3Φ AC fault		Inverter 1 side 2Φ AC fault		Inverter 1 side 1Φ AC fault	
		Inverter 1	Inverter 2	Inverter 1	Inverter 2	Inverter 1	Inverter 2	Inverter 1	Inverter 2
SC	**PI**	0.408	0.408	0.601	0.601	0.592	0.592	0.581	0.581
	FFPI	0.192	0.192	0.194	0.194	0.190	0.190	0.185	0.185
SVC	**PI**	0.421	0.421	0.614	0.614	0.605	0.605	0.594	0.594
	FFPI	0.195	0.195	0.201	0.201	0.196	0.196	0.190	0.190
STATCOM	**PI**	0.395	0.395	0.589	0.589	0.581	0.581	0.570	0.570
	FFPI	0.180	0.180	0.190	0.190	0.182	0.182	0.176	0.176
FC+SC	**PI**	0.397	0.397	0.597	0.597	0.587	0.587	0.575	0.575
	FFPI	0.185	0.185	0.189	0.189	0.186	0.186	0.181	0.181
FC+SVC	**PI**	0.405	0.405	0.609	0.609	0.597	0.597	0.585	0.585
	FFPI	0.190	0.190	0.196	0.196	0.191	0.191	0.186	0.186
FC+ STATCOM	**PI**	0.384	0.384	0.578	0.578	0.569	0.569	0.554	0.554
	FFPI	0.172	0.172	0.182	0.182	0.171	0.171	0.164	0.164

V. CONCLUSION

In this paper, a detailed transient performance analysis of an LCC-MTDC system feeding very weak AC networks was carried out with hybrid RPC's and firefly algorithm based optimal PI controller for rectifiers and inverters control. The various 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 very weak AC networks and MTDC systems under different operating environment. The HVDC transmission system model was simulated using Matlab software. 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 authenticate that the equal combination of FC+STATCOM has the steady and fastest response and display the superiority of firefly algorithm based PI controller over the conventional fixed gain PI controller. The harmonic analysis result also guarantees the quality of power supply at inverter AC side.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support and facilities provided by the authorities of the Annamalai University, Annamalainagar, Tamilnadu, India to carry out this research work.

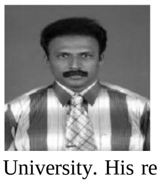
REFERENCES

1. S. Rüberg, A. L'Abbate, G. Fulli, A. Purvins, "Advanced Technologies for Future Transmission Grids-High-Voltage Direct-Current Transmission", Power Systems, Springer London, 2013, pp. 157-2133.
2. J. Reeve, "Multiterminal HVDC Power Systems", IEEE Transaction on Power Apparatus and Systems, vo1. 99 (2), 1980, pp. 729–37.
3. M. Callavik , M. Bahrman, P. Sandeberg, "Technology developments and plans to solve operational challenges facilitating the HVDC offshore grid", Proceedings of Power Energy Society General Meeting, 2012, pp. 1-6.
4. T. Sakurai, K. Goto, S. Irokawa, K. Imai, T. Sakai, "A New Control Method for Multi-terminal HVDC Transmission without Fast Communication Systems", IEEE Transaction on Power Apparatus and Systems, vol. 102, 1983, pp. 1140–1150.
5. A. Egea-Alvarez, J. Beerten, D. V. Hertem, O. G. Bellmunt, "Hierarchical power control of Multi-terminal HVDC grids" Electric Power Systems Research, vol. 121, 2015, pp. 207-215.

6. V. K. Sood, "HVDC and FACTS Controllers, Applications of Static Converters in Power Systems", Kluwer Academic Publishers, Boston, MA, 2004.
7. A. Gavrilovic, "AC/DC System Strength as Indicated by Short Circuit Ratios", IEEE International Conference on AC-DC Power Transmission, 1991, pp. 27-32.
8. S. Rao, EHV-AC HVDC Transmission and Distribution Engineering, Khanna publishers, New Delhi, India, 2003.
9. O. B. Nayak, A.N. Gole, "Dynamic Performance of Static and Synchronous Compensators at an HVDC Inverter Bus in a Very Weak AC System", IEEE Transactions on Power Delivery, vol. 9, no. 3, 1994, pp. 1350-1358.
10. C. Weindl, G. Herold, D. Retzmann, H. A, Cardona, I. A. Isaac, G. J. Lopez, "Feasibility of HVDC for Very Weak AC Systems with SCR below 1.5" IEEE International Conference on Power Electronics and Motion Control, 2006, pp. 1522- 1527.
11. Y. Zhuang, R. W. Menzies, "Dynamic Performance of a STATCON at the HVDC Inverter Feeding a Very Weak AC System", IEEE Transactions on Power Delivery, vol. 11, no. 2, 1996, pp. 958-964.
12. S. Singaravelu, S. Seenivasan, "Simulation Study of a Monopole HVDC Transmission System Feeding a Very Weak AC Network with Firefly Algorithm Based Optimal PI Controller", International Journal of Innovative Science and Modern Engineering, vol. 2, no. 11, 2014, pp. 1-9.
13. A. Routray, P. K. Dash, Sanjeev. K. Panda, "A Fuzzy Self-Tuning PI Controller for HVDC Links", IEEE Transactions on Power Electronics, vol. 11, no. 5, 1996, pp. 699-679.
14. P. K. Dash, A. Routary, S. Mishra, "A Neural Network based Feedback Linearising Controller for HVDC Links", Electrical Power Systems Research, vol. 50, no. 2, 1999, pp. 125-132.
15. N. Bawane, A. G. Kothari, D. P. Kothari, "ANFIS Based HVDC Control and Fault Identification of HVDC converter", HAIT Journal of Science and Engineering, vol. 2, no. 5-6, 2005, pp. 673-689.
16. X. Zhou, C. Chen, Fan Yang, M. Chen, "Optimization Design of Proportional-Integral Controllers in High-voltage DC System Based on an Improved Particle Swarm Optimization Algorithm", Electric Power Components and Systems, vol. 37, no. 1, 2009, pp. 78-90.
17. S. Seenivasan, S. Singaravelu, "Modelling and Simulation of Multiterminal HVDC Transmission System Feeding Strong AC Networks with Firefly Algorithm based Optimal PI Controller", Global Journal of Pure and Applied Mathematics, vol. 11, no. 2, 2015, pp. 579-590.
18. X. S. Yang, Engineering Optimization: An Introduction to Metaheuristic Applications, Wiley, 2010.
19. X. S. Yang, "Firefly Algorithms for Multimodal Optimization", Stochastic Algorithms: Foundations and Applications - Springer Berlin Heidelberg, vol. 579, 2009, pp. 169-178.
20. X. S. Yang, X. He, "Firefly Algorithm: Recent Advances and Applications", International Journal of Swarm Intelligence, vol. 1, 2013, pp. 36-50.
21. X. S. Yang, Z. Cui, R. Xiao, A. H. Gandomi, M. Karamanoglu, "Swarm intelligence and bio-inspired computation: Theory and applications", Amsterdam, Newnes, 2013.
22. C. Dufour, J. Mahseredjian, J. Belanger, "A Combined State-Space Nodal Method for the Simulation of Power System Transients", IEEE Transactions on Power Delivery, vol. 26, no. 2, 2011, pp. 928-935.

AUTHORS PROFILE

S. Seenivasan, received Bachelor of Engineering in Electrical and Electronics in 2005 and Master of Engineering in Power System in 2011 from Annamalai University, Annamalainagar, Tamilnadu, India. He is currently pursuing Ph.D. degree in the Department of Electrical Engineering, Annamalai University. At present, he is an Assistant Professor in the Department of Electrical Engineering at Annamalai University. His research interests are in high voltage DC transmission systems and soft computing techniques.



S. Singaravelu, received Bachelor of Engineering in Electrical and Electronics in 1990, Master of Engineering in Power System in 1992 and Ph.D. in 2007 from Annamalai University, Annamalainagar, Tamilnadu, India. At Present, he is a Professor in the Department of Electrical Engineering at Annamalai University. His research interests are in power electronics, power systems, electrical machines, wind/solar energy applications, high voltage DC transmission and smart grids.