Experimental Validation of Modular Transformer Converter Based Convertible Static Transmission Controller for Transmission Grid Management

Nima Yousefpoor, Ali Azidehak,
Subhashish Bhattacharya
ECE Department
North Carolina State University
Raleigh, NC, USA
{nyousef, aazideh, sbhattacharya}@ncsu.edu

Babak Parkhideh
Energy Production and Infrastructure Center
ECE Department
UNC-Charlotte
Charlotte, NC, USA
bparkhideh@uncc.edu

***Abstract*— For power flow control with specific attention to renewable energy resources based transmission in a meshed network, less complex coordinated control can be obtained with the proposed Convertible Static Transmission Controller (CSTC) concept which is connected across the substation power transformer and can be reconfigured to the required modes of operation. Convertible Static Transmission Controller (CSTC) is a versatile transmission controller which can perform several functions including power flow control for renewable resources transmission and transformer back-up for disaster management or life extension purposes. Different connecting configuration options (shunt-shunt, series-shunt, and series-series) can be obtained in the proposed transmission controller. In this paper, the control structure of CSTC in different modes of operation is presented, and dynamic performance of the CSTC based on the proposed control structures is further investigated in three different connecting configurations in PSCAD/EMTDC environment. Lab-scale experimental results are also presented to evaluate the performance of CSTC in three different modes of operation.**

***Index Terms*-- Power Flow Control, Renewable Transmission, Recovery Transformer, Modular Transformer Converter, Convertible Static Transmission Controller.**

I. INTRODUCTION

The US transmission grid is not yet prepared to accommodate the desired renewable resources specially the wind generations. One hurdle that impedes the investment in grid infrastructure and transmission capacity is intermittency nature of these sources. In fact, there is a common belief that commercially practiced renewable resources have less than 30% availability throughout the year [1]. On the other hand, due to the economic grounds, the integrations are often seen in the distribution and sub-transmission grids with naturally lower impedance than that of the transmission networks. This fact with high penetration of renewables causes overloading conditions that necessitate either network upgrade or curtailment in the generation while there is unutilized capacity in the transmission network, i.e. >138kV. Therefore, power flow controllers such as UPFC or BTB HVDC controllers become attractive albeit they are high cost solutions. Consequently, Transmission Owners (TO) confident with their system spare capacity are reluctant to invest in the available technologies such as Unified Power Flow Controller (UPFC) or Phase Shifting Transformer (PST) that may not have enough economical benefits to their systems. This paper explores a flexible static solution which can be retrofit to existing transmission assets, power transformer in particular- the main node of the power network [2]. A representative scheme of the Convertible Static Transmission Controller (CSTC) is presented in Fig. 1. In this scheme, the CSTC is installed across a transmission transformer to increase the system spare capacity and operating steady state and dynamic margins.

On the other hand, the transmission grid and its assets are getting aged especially in the US. A very familiar example of such assets is the power transformer, a very robust component of every power system. It has been reported that the average age of the transformers in the US is 40 years although most transformers are built for 30 years of operation. Looking into available equipment failure data, we can observe an increasing outage trend from 2008 to 2009 just due to transformer operational mechanism [3]. Specific attention to 300-399 kV class of transmission transformers reveals that 345 kV transformers need immediate attention and revised management [4]. The convertible static transmission controller can provide back-up in case of substation transformer failure or forced reduced transformer operation scenarios. It is worth noting that the required control can be embedded in the CSTC simplifying the power system operation, if the necessary commands are received from the main transformer [5]. This mode of operation is called distributed control vs. centralized control that may be requested in contingencies. In addition, the CSTC is desired to be transportable and compatible with different voltage levels and therefore operates as recovery transformer in case of natural and manmade hazards and disasters. In normal mode of operation, CSTCs are functioning to extend the life

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time of existing transformers by partially bypassing and conditioning the substation throughput power. In case of transformer failure, CSTCs can be deployed dispersedly or in an aggregated fashion to meet power, voltage, VAR and configuration requirements [6].

The objective of this paper is to analyze dynamic performance of CSTC in different modes of operation, and experimental results are also presented to verify the proposed control structure of CSTC in three different connecting configurations.

This paper is organized as follows. Section II explores the proposed modular transformer converter (MTC) based convertible static transmission controller (CSTC). Section III briefly explains the control structure of the CSTC in three modes of operation. Detailed dynamic performance analysis of the CSTC in different connecting configurations is presented in section IV. In section V, experimental results are presented to verify the controller performance under balanced operating conditions. Finally, Section VI presents the concluding remarks.

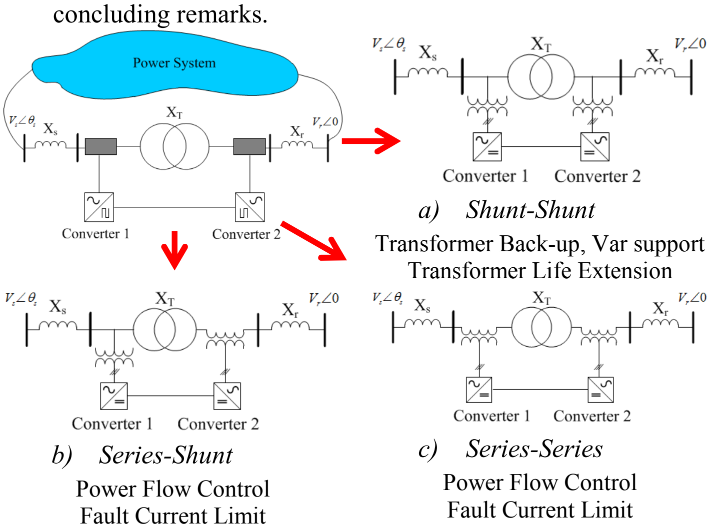


Fig. 1. Different modes of the Convertible Static Transmission Controller.

II. Modular Transformer Converter Based Convertible Static Transmission Controller

The Modular Transformer Converter (MTC) is a bidirectional back-to-back AC/AC conversion unit and the CSTC is a multi-functional transmission controller asset. To increase the voltage blocking capability and efficiency, multi-level converters have been proposed such as MMC of Siemens, [7] or CTLC of ABB, [8] which are still beyond wide spread deployment mainly because of the cost although minor engineering effort is claimed. In all the proposed topologies, MTC is desired to be implemented with minor engineering effort and possibly reduced costs through utilization of future standard AC/AC converters to be available in the market. The proposed CSTC with MTC building block is presented in Fig. 2 which different modes are realized through breakers operation. This option has potential to be developed for immediate market of US industry. MTC building blocks can be connected in series or parallel to achieve higher power. The interleaved modulation can be used to increase the effective switching frequency. An example of interleaved carrier waveforms for 4 MTC building blocks connected in series is shown in Fig. 3. The three-phase converter PWM output voltage waveform is illustrated in Fig. 4. The switching frequency for each converter is f_{sw}=*1500 Hz* whereas the effective switching frequency is f_{sw} *(effective)=4×1500=6000 Hz.* As a result, higher effective switching frequencies and lower converter losses can be obtained by the interleaved switching method.

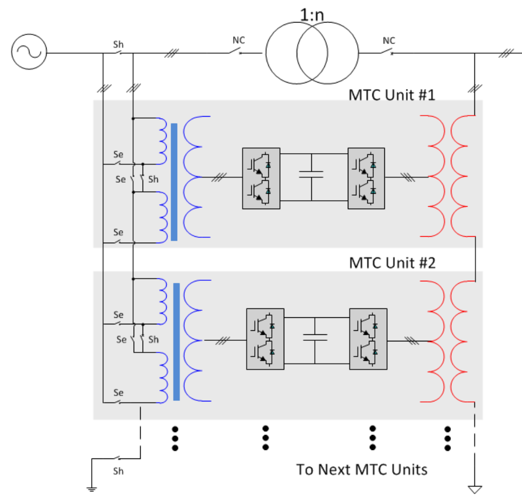


Fig. 2. Representative schematic of MTC based CSTC.

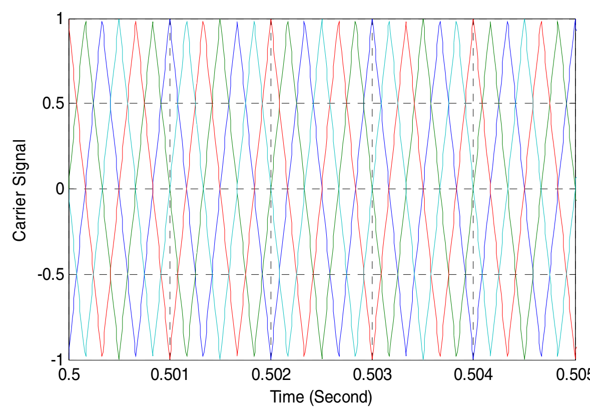


Fig. 3. Interleaved carrier waveform.

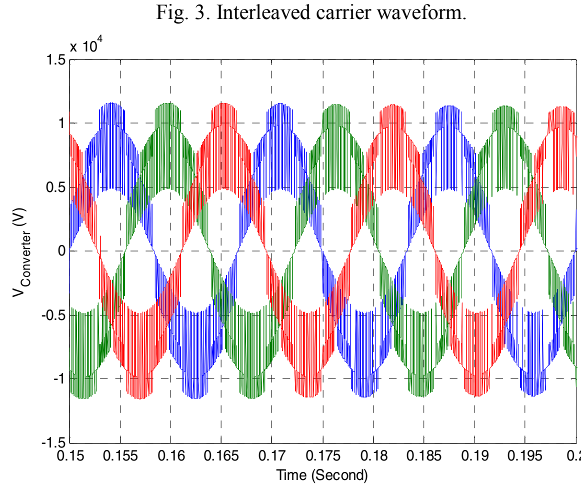
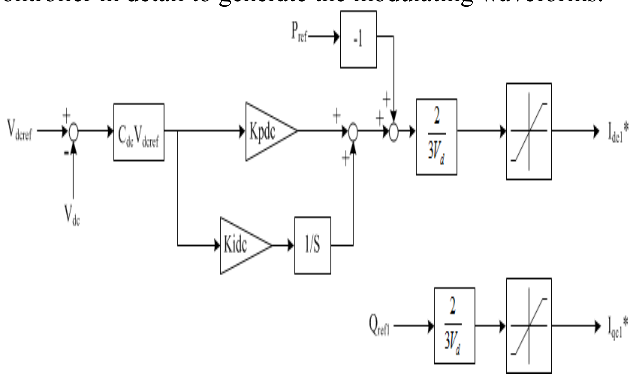


Fig. 4. Converter PWM output voltage waveform.

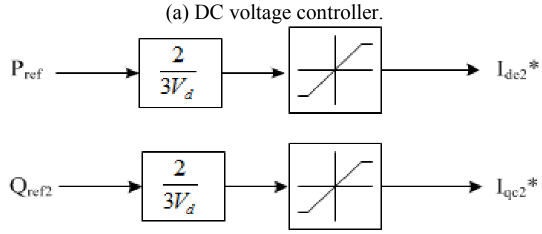
III. Control Structure of CSTC in Three Different Connecting Configurations

A. Shunt-Shunt Connecting Configuration

Fig. 5 shows the control scheme of the CSTC in shunt-shunt mode of operation. DC voltage controller generates the dq-axis current references (Fig. (5a)). The q-axis current reference can be calculated based on the reference value of reactive power. To improve the dynamic performance, the power reference can be used as a feed-forward signal in dc voltage control scheme. The current references are limited by the rated current of the switching devices. The second converter will control active and reactive power flow as it can be observed in Fig. (5b). Fig. 6 also shows the AC current controller in detail to generate the modulating waveforms.



(a) DC voltage controller.



(b) Power flow controller.

Fig. 5. Control Structure of CSTC in shunt-shunt mode of operation.

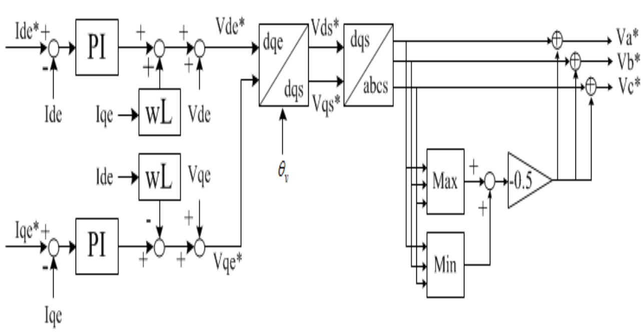
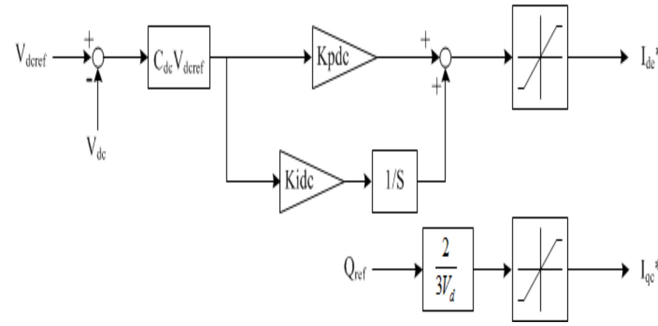


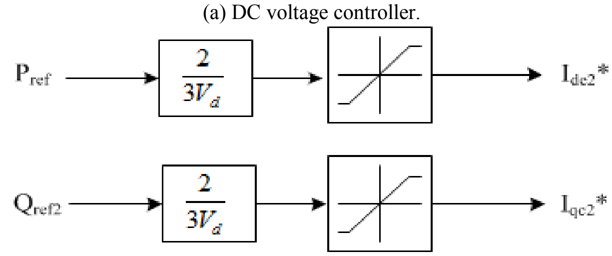
Fig. 6. Current Control Block.

B. Series-Shunt Connecting Configuration

The control structure of CSTC in series-shunt mode of operation is illustrated in Fig. 7. In this mode of operation, the series converter is used to control active and reactive power flow through the transformer, and the shunt converter maintains the bus voltage magnitude to the desired value by injecting or absorbing reactive power. The control structure in this mode is similar to the one used in conventional UPFCs.



(a) DC voltage controller.

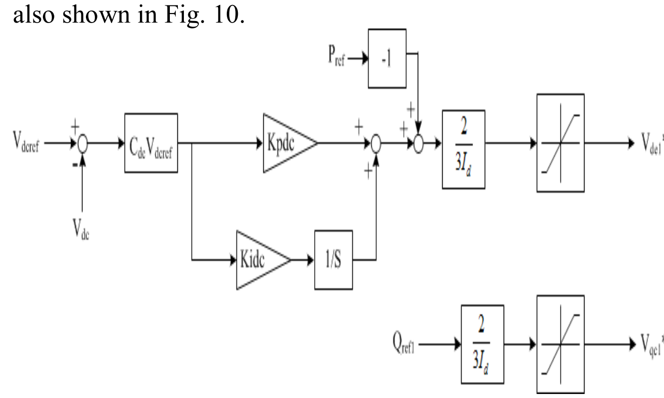


(b) Power flow controller.

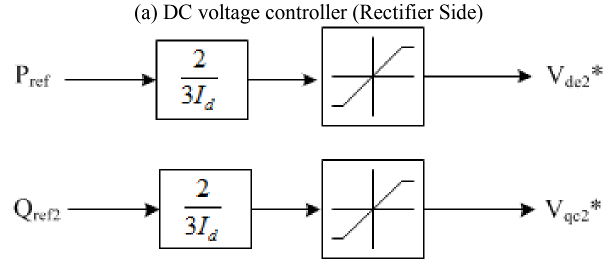
Fig. 7. Control structure of CSTC in series-shunt mode of operation.

C. Series-Series Connecting Configuration

The proposed control structure for series-series mode of operation is presented in Fig. 8. In this mode of operation, a measurement of the absolute phase angle of line current is needed. Zero phase sequence components should be removed from these signals, and line currents should be filtered before the control system can utilize them. The first step is to convert the ac signals into constant quantities. A DQ transformation process on line currents is performed in stationary reference frame. Then, current angle is calculated as it can be observed from Fig. 9. Voltage control block is also shown in Fig. 10.



(a) DC voltage controller (Rectifier Side)



(b) Power flow controller (Inverter Side)

Fig. 8. Control structure of CSTC in series-series mode of operation.

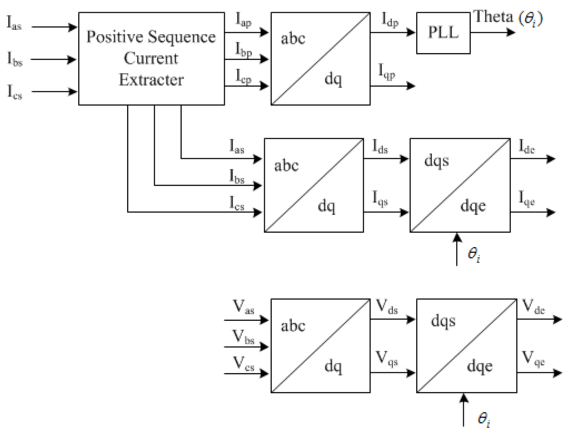


Fig. 9. Current angle extraction.

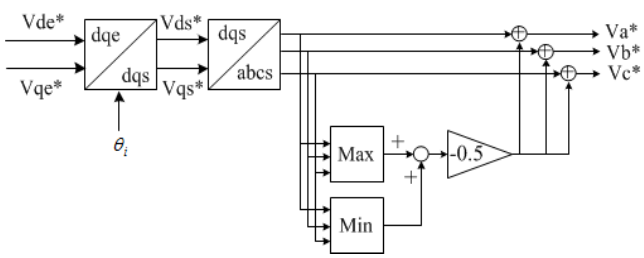


Fig.10. Voltage Control Block.

IV. Dynamic Performance Evaluation of the CSTC Through Simulation

A. *Shunt-Shunt Connecting Configuration*

In this section, the dynamic performance of the CSTC in shunt-shunt mode of operation is presented. PSCAD/EMTDC based simulation has been carried out to verify the control structure performance. CSTC as a recovery transformer can operate similarly to BTB HVDC converters. The CSTC in shunt-shunt mode of operation is used for power flow control. One converter operates in PQ mode and the other one is responsible to compensate for the losses and ensures a stable operation of the DC bus voltage while it supports its reactive power demands. The CSTC system parameters are tabulated in Table I.

Table I. CSTC System Parameters

Base Power	S	9 MVA
Line-to-line peak voltage	E	4.5 kV
Line frequency (grid)	f	60 Hz
Input voltage phase	θ_s	5.74°
sending-end Leakage inductance	L_s	0.1 pu=0.298 (mH)
Transformer inductance	L_T	0.1 pu=0.298 (mH)
receiving-end Leakage inductance	L_r	0.1 pu=0.298 (mH)
DC link voltage	V_{DC}	9 kV
DC link capacitance	C_{DC}	10 (mF)

DC capacitor voltage is shown in Fig. 11. As can be seen, the capacitor voltage is zero initially. For initial charging, the bypass-resistor is inserted between the AC grid and the CSTC converter. This resistor is used to reduce the initial charging current under the rated current of the CSTC converter. For start-up, all gating signals are initially off for 0s to 0.1s. From 0.1s, all controllers and gating signals are enabled to regulate dc voltage at 9 kV.

Dynamics of bidirectional active power flow is also displayed in Fig. 12. The reference active power is increased from zero to the rated power at 0.4s, and it is varied from 0 to -9 (MW) at 1.4s to show bidirectional active power flow through CSTC converter. Three phase ac current is shown in Fig. 13. A zoomed portion of three phase ac current is also depicted in Fig.14.

Fig. 15 shows dynamics of transformer and input reactive power flow when the reference value of reactive power for converter 1 has a ramp change from 0 to -9 (MVAR) at 0.4s, and it is changed from 0 to 9 (MVAR) at 1.4s. Dynamics of transformer and input reactive power flow with respect to converter 2 reactive power flow is also shown in Fig. 16.

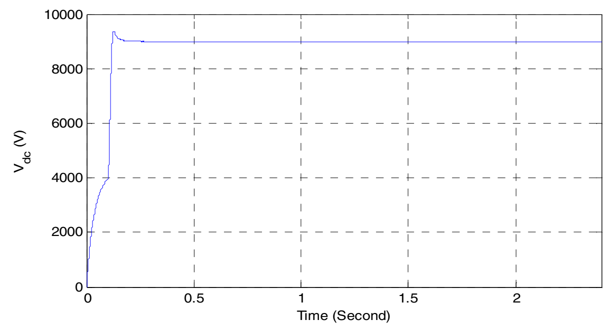


Fig. 11. DC capacitor voltage.

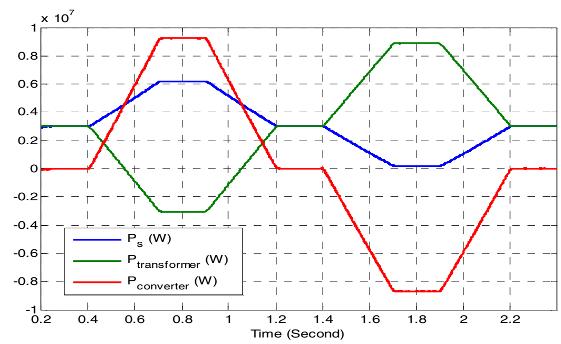


Fig. 12. Dynamics of bidirectional active power flow.

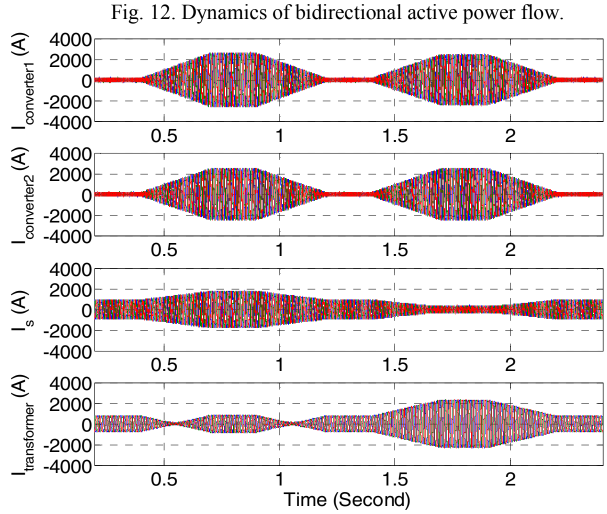


Fig. 13. Three phase ac current for bidirectional active power flow.

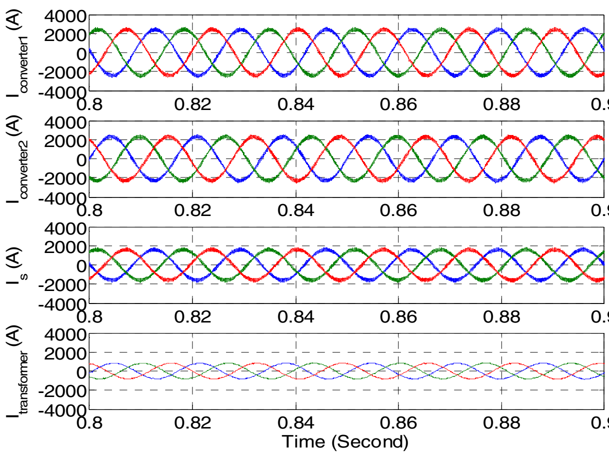


Fig. 14. A zoomed portion of three phase ac currents.

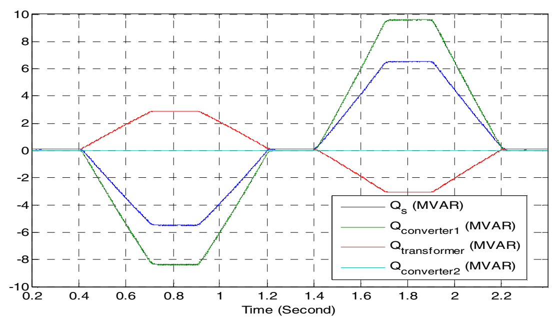


Fig. 15. Reactive power flow dynamics of converter 1 ($Q_{ref2}=0$).

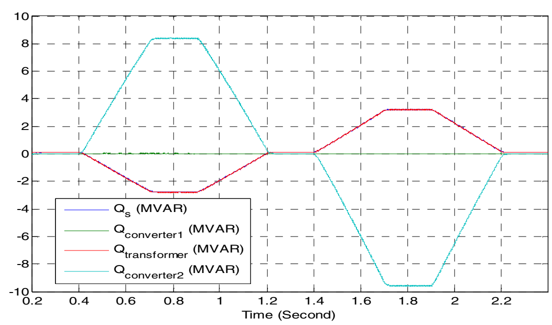


Fig. 16. Reactive power flow dynamics of converter 2 ($Q_{ref1}=0$).

B. Series-Shunt Connecting Configuration

In this section, the EMTDC simulation results of the MTC based CSTC system as the substation power flow controller in series-shunt mode of operation are presented. DC capacitor voltage is shown in Fig. 17. As can be seen, the dc us voltage is regulated at 9 kV.

Dynamics of transformer active power flow is also displayed in Fig. 18. The reference active power is increased from zero to -9 (MW) at 0.4s, and it is varied from 0 to the rated power at 1.4s to show bidirectional active power flow through CSTC converter. Transformer active power flow is equal to the input power flow, and it is regulated by converter 2 of CSTC converters which injects three-phase voltages in series. Three phase ac current for this case scenario is shown in Fig. 19.

Fig. 20 shows dynamics of transformer and input reactive power flow when the reference value of reactive power for converter 1 has a ramp change from 0 to -9 (MVAR) at 0.4s, and it is changed from 0 to the rated power at 1.4s. As can be seen, transformer reactive power is zero since the reference value of reactive power for converter 2 is equal to zero *($Q_{ref2}=0$)*. Dynamics of transformer reactive power flow with respect to converter 2 reactive power flow is also shown in Fig. 21. In this case, the reference value of converter 2 reactive power flow is varied from 0 to the rated power.

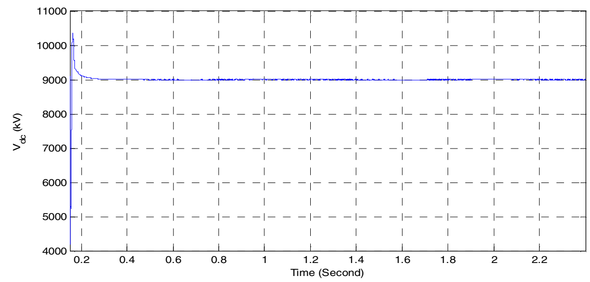


Fig. 17. DC capacitor voltage.

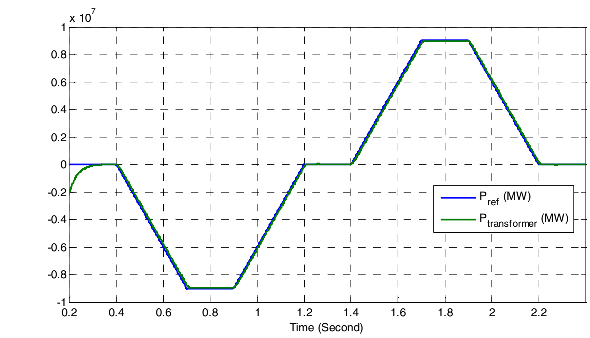


Fig. 18. Dynamics of transformer active power flow.

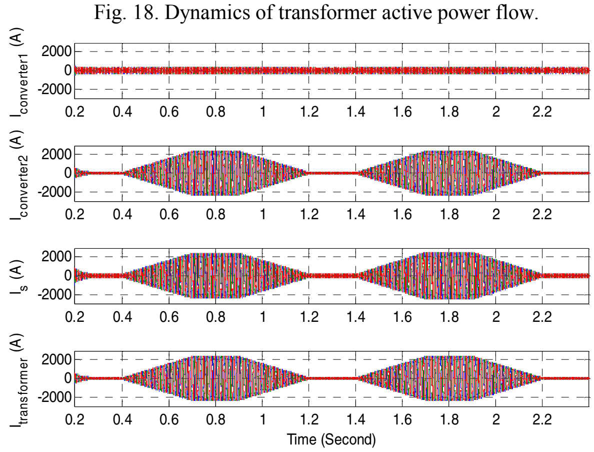


Fig. 19. Three phase ac current.

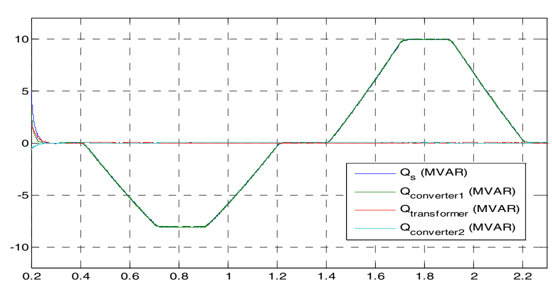


Fig. 20. Reactive power flow dynamics of converter 1 when converter 1 reactive power flow has a ramp change from 0 to rated power ($Q_{ref2}=0$).

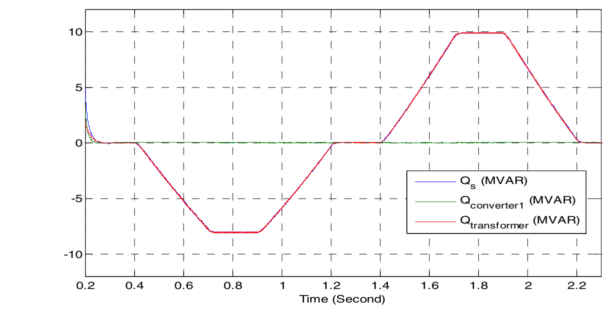


Fig. 21. Reactive power flow dynamics when converter2 reactive power flow has a ramp change from 0 to rated power ($Q_{ref1}=0$).

C. Series-Series Connecting Configuration

In this section, PSCAD/EMTDC based simulation has been carried out to verify the control structure performance for CSTC in series-series mode of operation. DC capacitor voltage regulated at 9 kV is shown in Fig. 22. Dynamics of transformer active power flow is also displayed in Fig. 23. The reference active power of CSTC converters is increased from zero to 5 (MW) at 0.4s, and it is varied from 0 to -5 (MW) at 1.4s to show bidirectional active power flow through CSTC converter. As can be seen, input active power flow is constant, and transformer active power flow is varied according to the reference value of CSTC active power flow. Three phase ac current is also shown in Fig. 24, and three-phase series injected voltage is shown in Fig. 25.

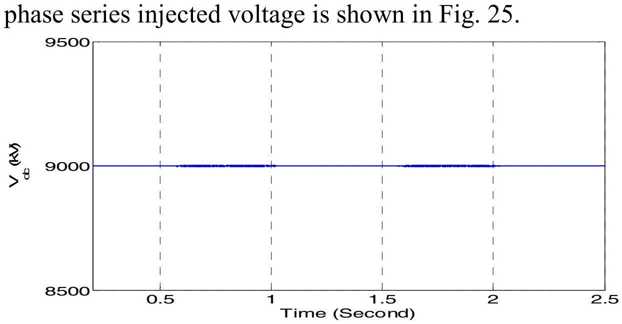


Fig. 22. DC capacitor voltage.

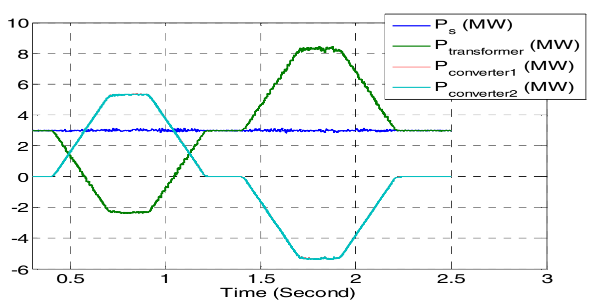


Fig. 23. Dynamics of transformer active power flow.

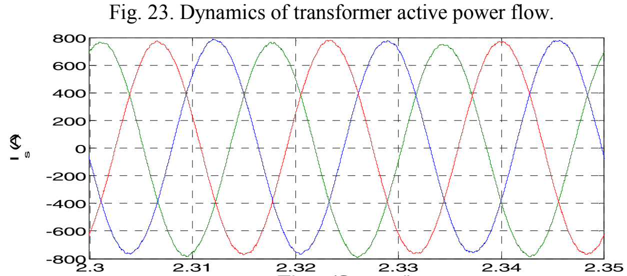


Fig. 24. Three phase ac current.

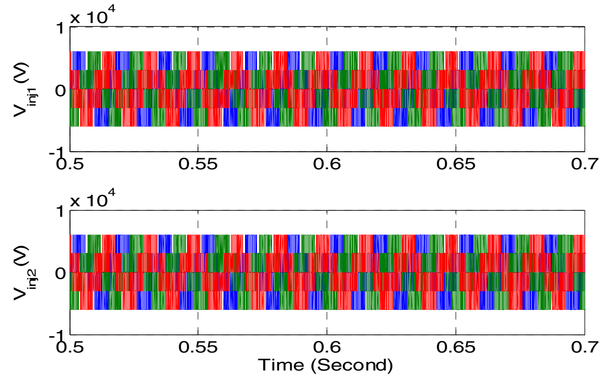


Fig. 25. Three-phase series injected voltage.

V. THE CSTC EXPERIMENTAL TEST BED

The schematic of the laboratory scale test-bed for CSTC system is shown in Fig. 26, and the CSTC experimental test bed is also shown in Fig. 27. The specifications of the experimental test bed can be summarized in Table. II. OZTEK controller is used to implement different control methods.

Three-phase input voltage and the extracted voltage angle is shown in Fig. 28. Fig. 29 shows dynamics of CSTC active power flow when it has a step change from 0 pu to 1 pu in shunt-shunt mode of operation. Fig. 30 shows dynamics of CSTC current. Dynamic performance of transformer and input current is also presented in Figs. 31, and 32 respectively when the reference value of CSTC active power flow has the step change from 0 pu to 1 pu. Fig. 33 shows dynamics of reactive power flow when the reference value of converter 1 reactive power flow has a step change from 0 pu to -1 pu. Dynamics of converter 2 reactive power flow is also shown in Fig. 34 when it has a step change from 0 pu to 1 pu.

The dynamic performance of transformer active power flow in series-shunt mode of operation is presented in Fig. 35 when the reference value of CSTC active power flow has a step change from 0 pu to 1 pu. Three phase transformer ac current is shown in Fig. 36. Fig. 37 shows dynamics of transformer reactive power flow when the reference value of reactive power for converter 2 has a step change from 0 to 1 pu. Transformer current is also shown in Fig. 38 for this case scenario. DC bus voltage is also shown in Fig. 39.

Dynamics of transformer active power flow in series-series mode of operation is also displayed in Fig. 40. The reference active power of CSTC converters is increased from 0 pu to 2 pu. Transformer three phase ac current is also shown in Fig. 41.

Table II. Specifications of Experimental Test Bed

Line-to-line peak voltage	E	208 V
Line frequency (grid)	f	60 Hz
sending-end Leakage inductance	L_s	5 (mH)
Transformer Leakage inductance	L_T	5 (mH)
receiving-end Leakage inductance	L_r	5 (mH)
Switching frequency	f_{sw}	10 (kHz)
Converter Transformer	S_c	15 (kVA)
MTC transformer	S_T	5 (kVA)

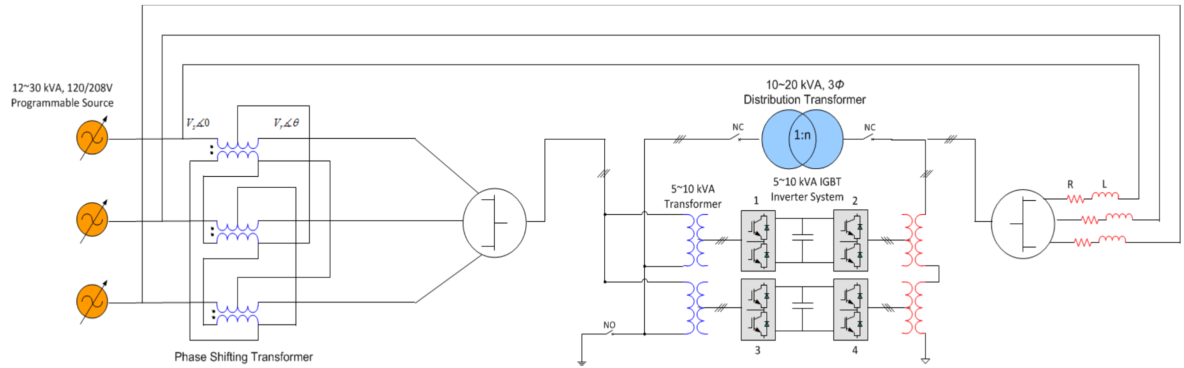


Fig. 26. Schematic of the laboratory scale test-bed for CSTC system.

Fig. 27. Experimental test-bed for CSTC system

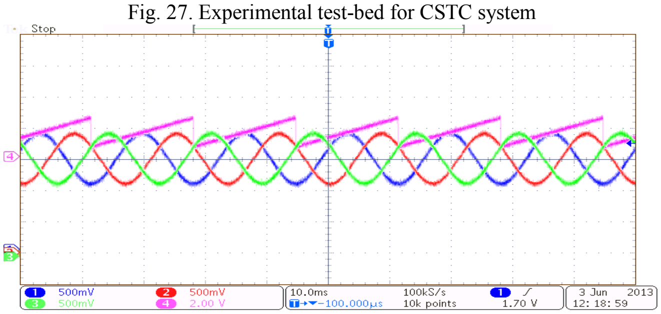


Fig. 28. Three-phase input voltages and extracted voltage angle

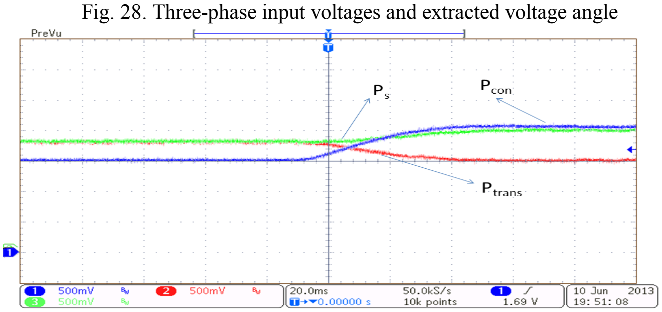


Fig. 29. Dynamics of active power flow when the reference value of active power has a step change from 0 pu to 1.0 pu (shunt-shunt mode)

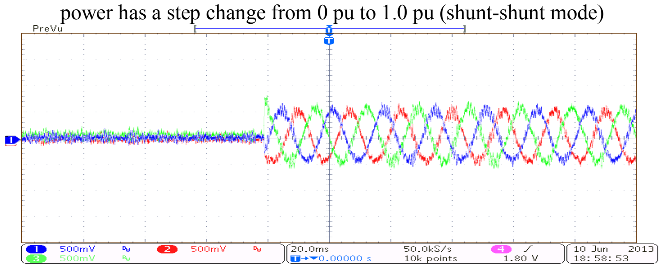


Fig. 30. Dynamics of converter current when active power flow has a step change from 0 pu to 1.0 pu (shunt-shunt mode)

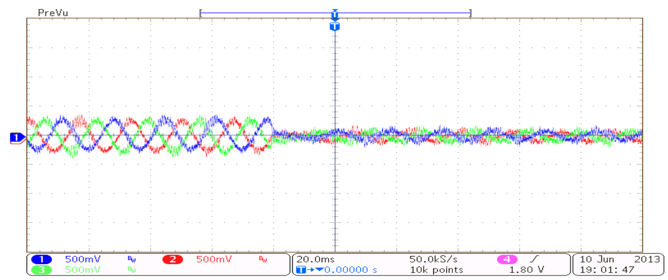


Fig. 31. Dynamics of transformer current when active power flow has a step change from 0 pu to 1.0 pu (shunt-shunt mode)

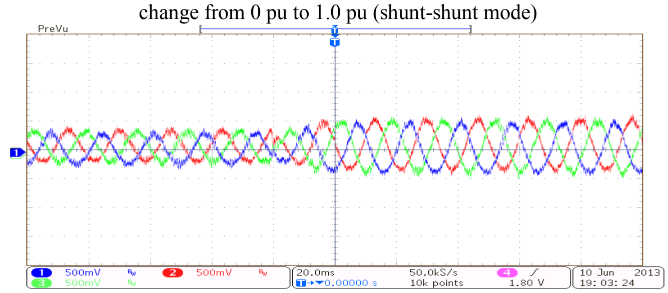


Fig. 32. Dynamics of input current when active power flow has a step change from 0 pu to 1.0 pu (shunt-shunt mode)

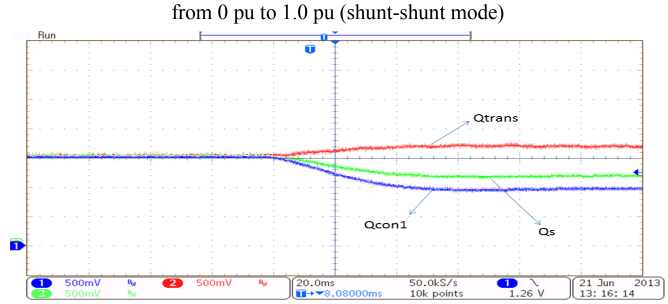


Fig. 33. Dynamics of converter1 reactive power flow when it has a step change from 0 pu to -1.0 pu (shunt-shunt mode)

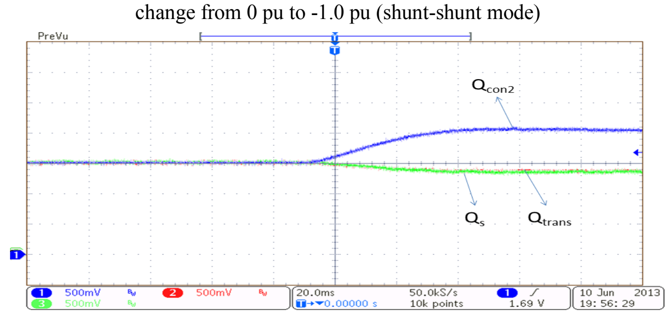


Fig. 34. Dynamics of converter2 reactive power flow when it has a step change from 0 pu to 1.0 pu (shunt-shunt mode)

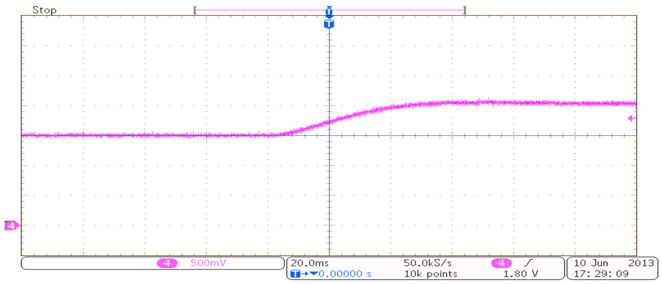


Fig. 35. Dynamics of transformer active power flow when it has a step change from 0 pu to 1.0 pu (series-shunt mode)

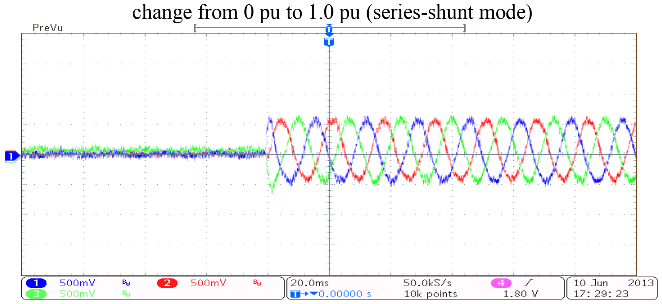


Fig. 36. Dynamics of transformer current when active power flow has a step change from 0 pu to 1.0 pu (series-shunt mode)

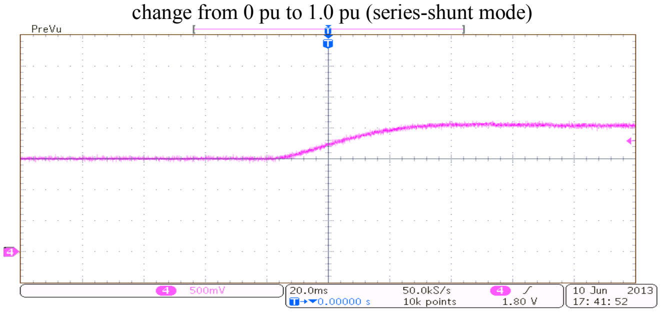


Fig. 37. Dynamics of transformer reactive power flow when the reference value of converter 2 reactive power flow has a step change from 0 pu to 1.0 pu (series-shunt mode)

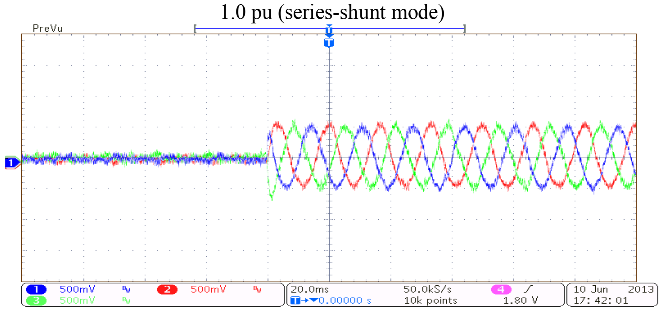


Fig. 38. Dynamics of transformer current when converter 2 reactive power flow has a step change from 0 pu to 1.0 pu (series-shunt mode)

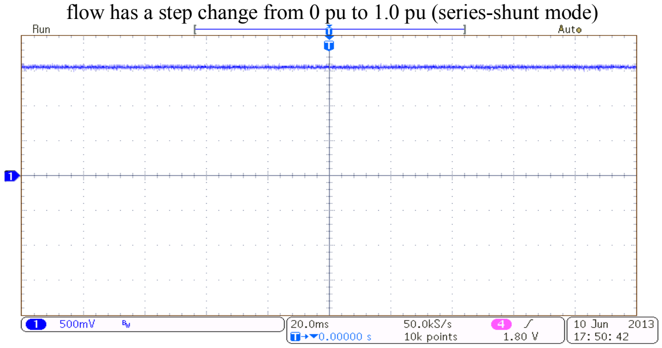


Fig. 39. DC bus voltage (series-shunt mode)

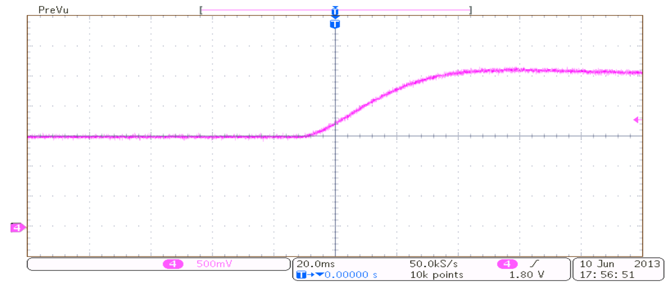


Fig. 40. Dynamics of transformer active power flow when it has a step change from 0 pu to 2.0 pu (series-series mode)

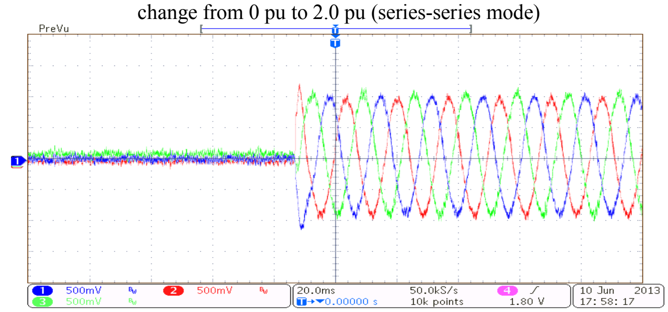


Fig. 41. Dynamics of transformer current when active power flow has a step change from 0 pu to 2.0 pu (series-series mode)

VI. Conclusion

Existing FACTS solutions enable dynamic control for the transmission lines; however, the CSTC concept provides the flexibility of full or partial utilization for the transmission lines and power transformers. This flexibility effectively increases the system spare capacity and operating margins, and also provides back-up in case of power transformer failure scenarios by providing real-time continuous power flow control. This paper presents the dynamic performance of the CSTC for different operation modes. Experimental results have been shown to verify the performance of the CSTC in three different connecting configurations.

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