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### Hybrid Converter-station Transformer for Enhanced HVDC Robustness

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#### **SUMMARY**

The HVDC transmission is gaining wider popularity due to the exponential integration of renewable energy resources that are typically located far from the load centres. In addition, the HVDC bears advanced control features and the capability to interconnect asynchronous AC networks. Amongst the two most popular HVDC technologies, VSC-HVDC and LCC-HVDC, the former has superior control capabilities and does not rely on synchronous machines for commutation. However, it suffers from higher losses due to the involvement of high-speed switching, requires complex gate-drive circuitry and bears weak overload capability. On the other hand, LCC-HVDC is a highly mature and simpler technology that is available in higher ratings. However, its operation is dependent upon strong interconnected AC network with any inverter or rectifier station disturbance leading to commutation failure and ultimate grid collapse. Our work is focussed on enhancing the reliability and reduced control complexity of the LCC-HVDC technology. We propose the conversion of the inverter-side substation transformer into a hybrid transformer through the integration of a power-electronics based module between its neutral and substation ground. The proposed device introduces a variety of advanced features in conventional converter-station transformers. These include voltage regulation, harmonics isolation, voltage and impedance balancing and power flow control. In addition, the device protects the HVDC system from collapse due to DC flow in adjacent AC network that could half-cycle saturate the converter-station transformers. The DC flow could result from geomagnetic disturbances (GMDs), HVDC monopolar or ground return (GRM) operation or due to non-ideal switching in power-electronics based resources. The proposed device bears superiority over the existing solutions that include utilization of flexible alternating current transmission system (FACTS) devices on inverter side AC bus and complex controller-enhancement strategies. This is conceivable through its simpler operating principle and its installation between the transformer neutral and substation ground that helps to avoid exceeding the basic insulation level (BIL) of the converter-station transformer, one of the major concerns with the floating FACTS devices. The proposed strategy has been evaluated on the CIGRE HVDC benchmark model, where the results verify its promising performance in enhancing robustness of the HVDC transmission systems.

#### **KEYWORDS**

DC-AC converter, HVDC transmission, impedance matching, power flow control, power system reliability, power quality.

## 1. INTRODUCTION

The high voltage DC (HVDC) transmission has highly advantageous features, such as, bulk power transmission capacity with minimal loss, enhanced reliability and control. This has increased the significance of HVDC transmission in the current and future grid due to the rapid integration of volatile renewable resources and the requirement to deliver power from remote generation sites to load centers. The line commutated converter HVDC (LCC-HVDC) is the most utilized transmission technology due to its simpler operation, wider maturity and availability in higher ratings. However, it suffers from issues like dependence upon strong connected AC system and commutation failure (CF) resulting from faults on the inverter side [1], [2]. A myriad of solutions has been proposed in previous works to mitigate the risk of CF in LCC-HVDC. These solutions can be divided into three groups: a) reactive power compensation strategies utilizing flexible alternating current transmission system (FACTS) devices on inverter-side AC bus, such as, unified power flow controller (UPFC), static synchronous compensator (STATCOM) and static VAR compensator (SVC) [3]-[6], b) power-electronics strategies [7], c) controller-enhancement strategies [8], [9]. However, these strategies either lead to higher investment cost due to integration of compensation devices at nominal voltage or more control complexity. The availability of strong AC system for reliable LCC-HVDC operation may get compromised due to the flow of DC or quasi-DC on the inverter-side AC grid. This could be the result of HVDC monopolar or ground return mode (GRM) operation [10], [11], solar storms or geomagnetic disturbances (GMDs) [12], high-elevation nuclear pulse (HEMP) attacks [13], or due to non-ideal switching in inverter-based resources. The resultant DC could lead to half-cycle saturation of converter transformers that are typically operated close to their full rating for efficiency and optimum resource utilization. This results in large, highly distorted and asymmetric transformer magnetizing current that leads to immense reactive power absorption, transformer internal heating and maloperation of the installed protection equipment [14], [15]. The effect of DC on LCC-HVDC systems has been studied widely, where they have proven to be the cause of CF and overloading of harmonic filters [16], [17]. The most proposed strategy to limit DC from flowing in AC transmission systems is the use of neutral blocking devices (NBDs) between the neutral and converter station ground of transformers.

This paper proposes an enhanced version of the novel transformer conversion strategy presented in [18] and its application to HVDC systems. It is related to a hybrid-smart transformer developmental strategy that aims at enhanced grid reliability and resiliency by converting the traditional converter-transformers on HVDC inverter-side substations into smart transformers. This objective is achieved through integration of a power electronics-based device between the neutral and ground of converter transformers. The device introduces multiple advanced features in conventional transformers, such as, harmonics isolation, voltage and impedance balancing, voltage regulation and power flow control. This provides enhanced HVDC system robustness against disturbances on the AC grid, such as, faults or DC flow. The granular voltage control capability introduced by the proposed device in converter transformers could be utilized to minimize tap utilization for DC voltage control when the thyristors are already at their rated firing angle. Also, this device could eliminate the asymmetrical firing angle of valves resulting from AC grid unbalance. The integration of the proposed device in the transformer neutral averts exceeding the basic insulation level (BIL) of transformers that is the biggest concern during the installation of floating power electronics for similar objectives.

The rest of the paper is organized as follows: Section II introduces the proposed HVDC transformers conversion strategy and the system utilized to evaluate this approach. The section III presents the results from simulations performed in PSCAD/EMTDC. Finally, the paper is concluded with some future directions in section IV.

## 2. PROPOSED APPROACH AND SYSTEM UNDER STUDY

### *2.1. Proposed Hybrid Smart Transformer Strategy*

The strategy proposed in this paper is related to the conversion of traditional transformers on inverter side of HVDC systems into hybrid-smart transformers. This conversion is performed utilizing a transformerless

power electronics-based device integrated between the neutral of power transformers and converter-station ground. The single-phase version of the proposed scheme is depicted in Fig. 1, where it employs an H-bridge converter with a capacitor  $C_2$  and energy storage on the DC side and a high frequency LC filter comprising of capacitor  $C_1$  and inductor  $L_1$  on the AC side. The converter can inject voltage with varying magnitude and phase angle between the transformer neutral and ground to perform different smart functionalities; voltage regulation and balancing, impedance control, power flow control and harmonics isolation as shown in Fig. 2. The block diagram of PWM generation for the proposed scheme is shown in Fig. 3, where the top branch performs voltage regulation or balancing. The second branch is dedicated to impedance balancing, where the gain  $G_1$  adjustment leads to desired impedance control objective. The third branch performs harmonics isolation by extracting harmonics ( $V_h$ ) from  $V_{PCC}$  utilizing a second order generalized integrator phase locked loop (SOGI-PLL) and later these harmonics are injected between the two converter-connection terminals. The last branch performs decoupled active/reactive power flow across the transformer by adjusting the gain  $G_2$ . In this way, the proposed module enables a traditional transformer to perform a myriad of enhanced smart control functionalities utilizing a converter rated to 25-30% of nominal voltage. In order to protect the proposed module against overvoltages and to avoid exceeding the transformer BIL during ground faults, inrush-current flow, transient recovery voltages (TRV), load imbalances, circulating currents and ferro resonance, the module is accompanied with a high-speed bypass switch. The switch is operated utilizing a signal from an overvoltage (OV) relay sensing the voltage ( $V_o$ ) between the transformer neutral and converter-station ground. The converter transformers are typically three phase assembled by utilizing three-single phase transformers in desired configuration that eases replacement and transportation. Accordingly, the smart transformer design for three-phase power systems is presented in Fig. 4, where the proposed module is integrated between the neutral of each single-phase transformer and converter-station ground.

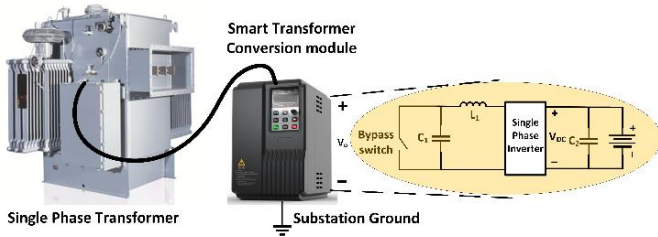


Fig. 1. Proposed hybrid smart converter transformer.

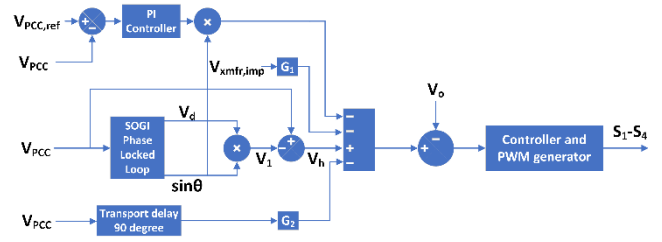


Fig. 3. PWM generation for the smart transformer conversion module.

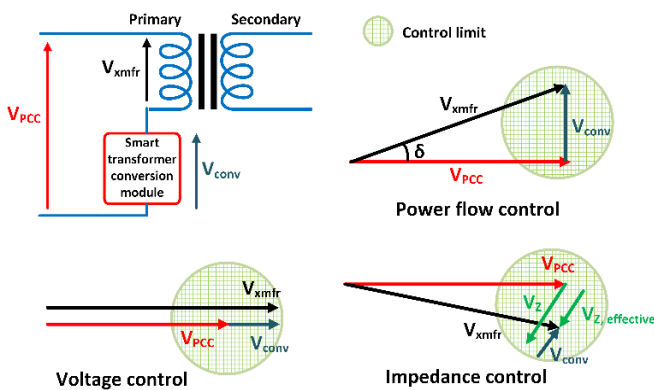


Fig. 2. Control strategy for the smart transformer conversion module.

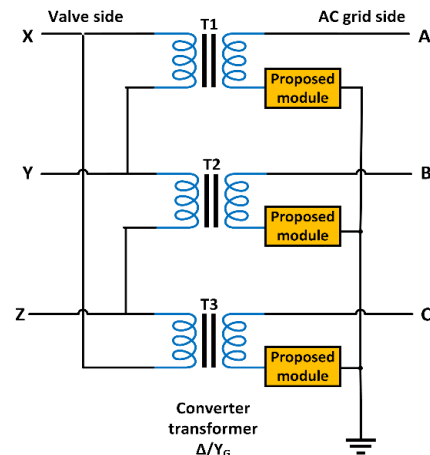


Fig. 4. Proposed scheme for the three-phase hybrid smart converter transformer (delta/gye-grounded configuration).

## 2.2. System Under Consideration

The test system utilized to verify the proposed approach is the CIGRE HVDC benchmark model that is a monopolar, 500kV, 1000MW link equipped with 12-pulse converters on both rectifier and inverter side. There are also damped filters and capacitive reactive compensation on both sides. The AC system

comprises of filters, transformers and supply network connected to each side of HVDC converter. The CIGRE HVDC benchmark model represents a weak system where the term short circuit ratio (SCR) is used to define the weakness of an AC/DC node. The SCR is defined as the ratio of short circuit capability of the AC system to the DC link power, where the weak systems have a SCR between 2.0 and 3.0. The prominent parameters of the CIGRE benchmark model are presented in table 1. The traditional transformers in the CIGRE benchmark model are converted into hybrid-smart transformers to perform advanced functionalities, such as, voltage regulation, harmonics isolation, voltage and impedance balancing beyond mere voltage conversion and isolation. The modified CIGRE HVDC benchmark model is shown in Fig. 5. The proposed smart transformer conversion strategy is also utilized to provide enhanced power flow control functionalities on AC-tie lines in the parallel AC/DC networks. Therefore, the proposed strategy could be employed to efficiently control power flows across the AC transmission corridors in the current scenario of exponential integration of volatile distributed energy resources (DERs). This would in turn lead to optimum utilization of AC transmission capacity and reduced congestion across certain corridors thus avoiding DER curtailment and inefficient operation.

TABLE I. CIGRE HVDC BENCHMARK MODEL PARAMETERS

LCC-HVDC system rated parameters: 500kV, 1000MW, 50Hz, DC side: R=5Ω, L=1.2H						
AC system (Rectifier side)	Reactive power compensation capacity (Rectifier side)	Converter transformer (Rectifier side)	AC system (Inverter side)	Reactive power compensation capacity (Inverter side)	Converter transformer (Inverter side)	Short Circuit Ratio (SCR)
382.8kV 47.7 ∠84.25° Ω	626MVA	603.7MVA 345/213.5kV 0.18pu	215kV 21.2 ∠75° Ω	626MVA	591.8MVA 230/209.2kV 0.18pu	2.5

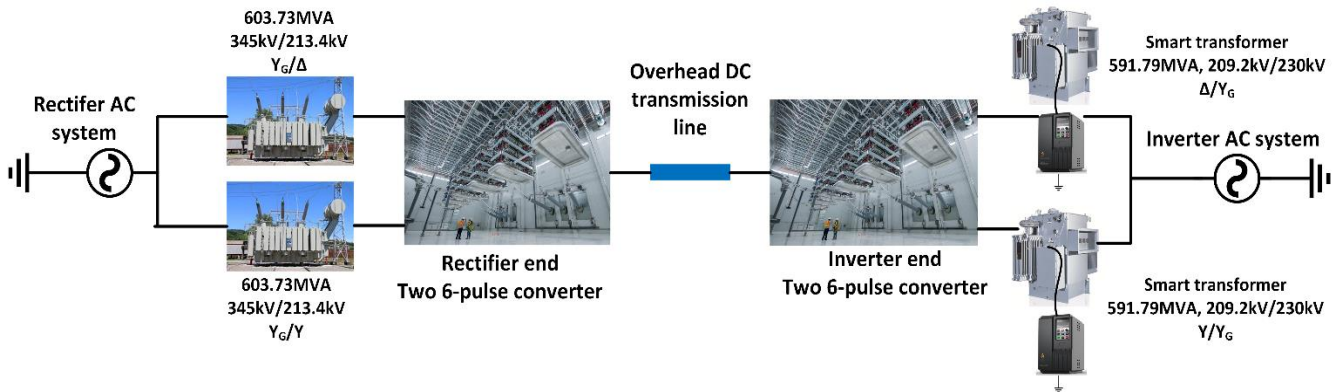


Fig. 5. Modified CIGRE benchmark model.

### 3. SIMULATION RESULTS

The smart functionalities of the proposed hybrid smart transformer configuration are evaluated in PSCAD/EMTDC. The module parameters utilized for current study are presented in table 2.

TABLE II  
PARAMETERS OF PROPOSED MODULE

Circuit Component	Component value
C <sub>1</sub>	100uF
C <sub>2</sub>	2.3mF
L <sub>1</sub>	1mH
V <sub>DC</sub>	80kV

#### 3.1. Voltage Regulation

The voltage regulation capability of the proposed module is aimed at restoring and maintaining the AC-bus voltage during faults or temporary disturbances on the main grid to avoid commutation failure and to reduce DC power recovery time. This functionality is depicted by simulating a three-phase to ground fault of 3-cycles on the inverter-side AC bus at 0.5s with the proposed module deactivated and repeating

with the proposed module in activated state. The result with the proposed module deactivated for a three-phase fault on AC grid on inverter side is shown in Fig. 6. The Fig. 7 (a) presents the AC voltage on transformer primary terminals during the simulated three-phase fault with the proposed module activated. It is observed that the module retains the transformer voltage during the fault to pre-fault level. The compensation signal from the proposed module for this scenario is shown in Fig. 7 (b).

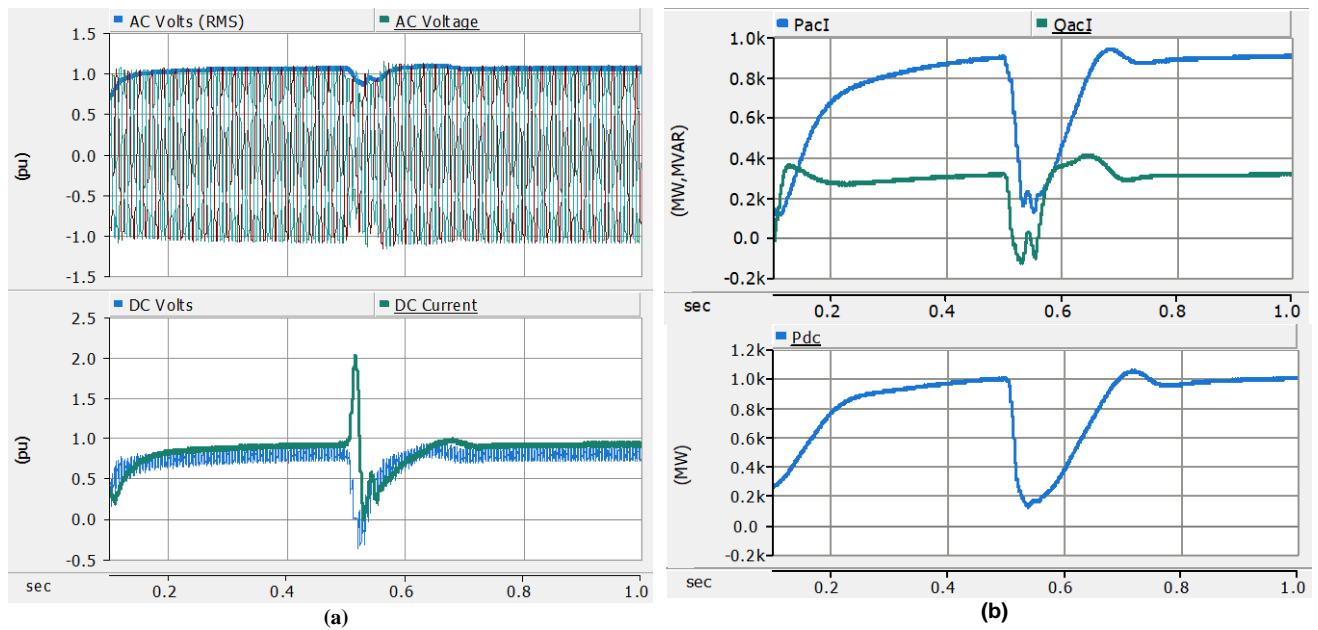


Fig. 6. (a) AC/DC voltage and current (b) AC/DC power for a three-phase to ground fault on inverter-side AC bus.

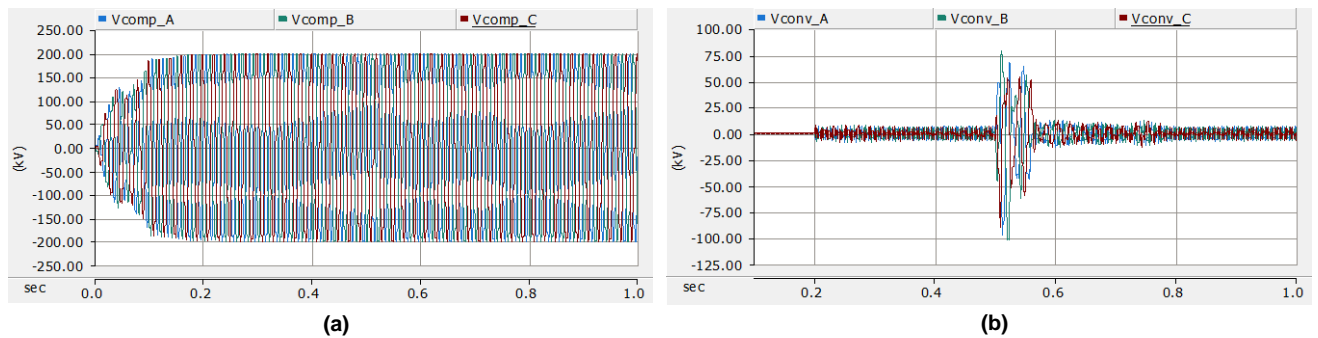


Fig. 7. (a) Compensated converter-transformer primary voltage, (b) Compensation signal applied by the proposed module for a three-phase to ground fault on inverter-side AC bus.

The voltage regulation or balancing capability of the proposed hybrid-smart transformer configuration leads to enhanced transient stability of the HVDC systems leading to improved power system reliability and resiliency.

### 3.2. Harmonics Isolation

In order to present the harmonics isolation capability of the proposed approach, the inverter AC system is assumed to be undergoing a GMD or HEMP event. This is simulated by integrating a DC source between the neutral and ground of the inverter AC system source, that leads to half-cycle saturation of upper converter transformer (both upper and lower are identical) as shown by the non-symmetrical B-H curve and deep half-cycle saturation in Fig. 8 (a). Similarly, the magnetizing current is non-symmetrical along the horizontal axis with its peak value reaching multiple times that during no DC injection as shown in Fig. 8 (b).

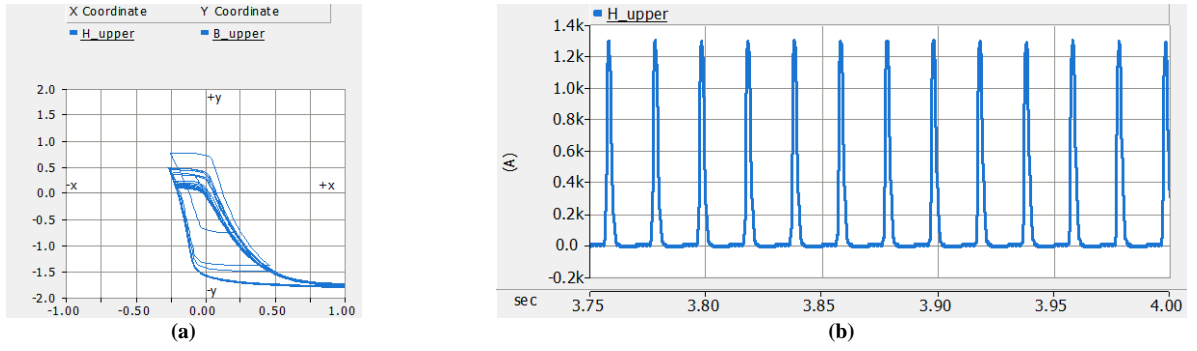


Fig. 8. (a) B-H curve of upper converter transformer with DC injection, (b) Magnetizing current of upper converter transformer with DC injection.

As a result of half-cycle saturation of the converter transformer, harmonics are introduced in the primary AC voltage of the converter transformer. Also, it leads to oscillations on the DC bus and resultant DC power flow also drops to a very low value of 600MW from 1000MW. The proposed module injects the harmonics on AC bus voltage between its two connection points that leads to their isolation from travelling towards the transformer primary terminals according to the concept discussed in detail in [12]. The compensation signal for the above presented DC injection scenario is shown in Fig. 9. This leads to enhanced HVDC reliability against DC or harmonics flow on the adjacent AC grid.

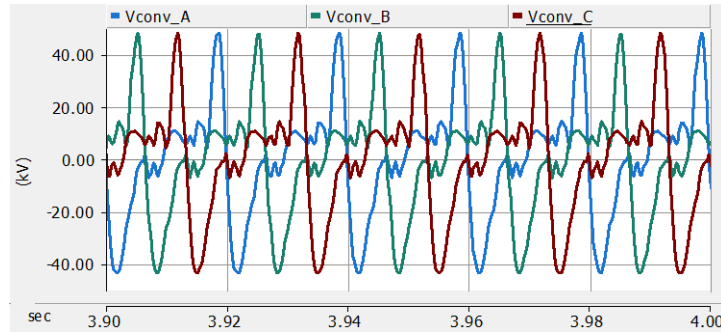


Fig. 9. Compensation signal applied by the proposed module to avoid converter transformer half-cycle saturation.

### 3.3. Power Flow Control

There is an increasing trend of parallel AC/DC transmission in China and Europe to utilize the already installed resources while enhancing the power transmission capability of the corridor. The HVDC transmission has the inbuilt characteristic to perform power flow control, however, the AC-tie lines lack this capability. This leads to congestion across certain AC-tie lines that leads to under-utilized operation of other tie-lines. This leads to inefficient operation through curtailment of renewable generation resources that is highly undesired. In this regard, the proposed module bears the capability to provide decoupled active/reactive power flow across the AC-tie lines through conversion of associated traditional transformers into hybrid-smart transformers. The concept of decoupled P, Q control between PCC and transformer primary for the system shown in Fig. 2 is given as:

$$P = \frac{3|V_{PCC}||V_{xmfr,eq}|\sin(\delta_{PCC} - \delta_{xmfr,eq})}{Z_{xmfr}} \quad (1) \quad Q = \frac{3(|V_{PCC}|^2 - |V_{xmfr,eq}|^2)\cos(\delta_{PCC} - \delta_{xmfr,eq})}{Z_{xmfr}} \quad (2)$$

Here,  $V_{xmfr,eq}$  is the addition of transformer and converter voltage,  $\delta_{PCC}$  and  $\delta_{xmfr,eq}$  are the respective angles of  $V_{PCC}$  and  $V_{xmfr,eq}$ . As, the proposed strategy provides independent control of the converter voltage and phase angle, the  $V_{xmfr,eq}$  and  $\delta_{xmfr,eq}$  could be attuned individually. This leads to decoupled active and reactive power flow control. In order to verify the working of this power flow control approach, an AC tie-line is connected parallel to the CIGRE HVDC benchmark model as shown in Fig. 10. The 1000MW power gets distributed across the two networks according to their parameters as shown in Fig. 11 (a). Later, the gain  $G_2$  is adjusted to -0.1 that leads to 50 MW drop in AC tie-line. Similar

modules could be utilized to control power flow across multiple AC-tie lines leading to optimum resource utilization and efficient grid operation.

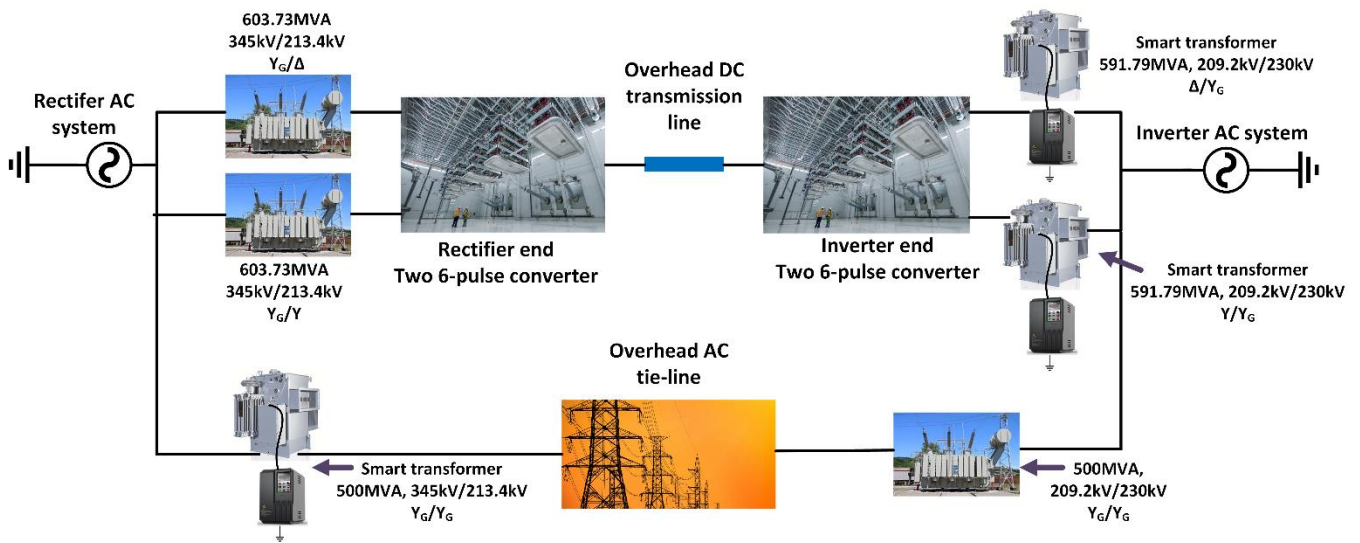


Fig. 10. Modified CIGRE benchmark model to depict power flow control.

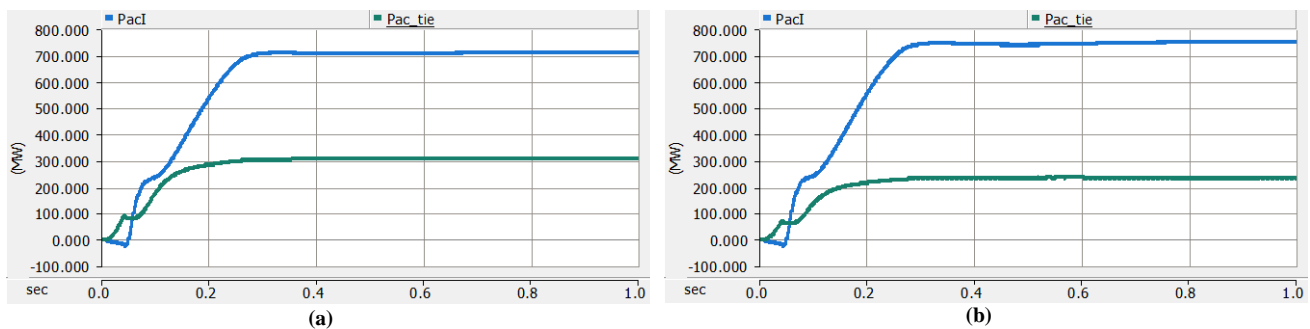


Fig. 11. (a) Without power flow control (b) With power flow control activated.

#### 4. CONCLUSIONS AND FUTURE WORK

In this paper, transformation of conventional converter transformer into a hybrid smart transformer has been proposed by integrating a transformerless power-electronics based module between its neutral and converter-station ground. The proposed device enhances the functionalities of converter transformer beyond voltage conversion and isolation by enabling voltage regulation, harmonics isolation and voltage/impedance balancing. This device can also be integrated with substation transformers connected to AC-tie lines in parallel AC/DC transmission to enable power flow control in AC lines. The simulation results depict the promising performance of the proposed configuration to perform the above discussed smart functionalities utilizing the CIGRE HVDC benchmark model, thus providing an all-in-one solution to multiple HVDC problems. The practical implementation of the proposed module requires devices with high-blocking voltage and switching speed for which wide band gap (WBG) silicon carbide (SiC) based MOSFETs could be utilized as they have already been demonstrated in the range of 10kV-24kV. The future work involves the verification of the proposed approach through development of a hardware prototype and proposing a modular multilevel converter (MMC) configuration for practical implementation of the proposed scheme on real HVDC converter stations.

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