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Power System Compensation Using a Power Electronics Integrated Transformer

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Abstract—This paper presents a new transformer, i.e., the Custom Power Active Transformer (CPAT) - which integrates shunt and series equivalent circuits within the transformer's magnetic structure. Thus, it provides power system services using a single transformer. The CPAT equipped with a power converter can be utilized in distribution systems to control grid-current and load-voltage waveforms while operating as a step-up or step-down transformer between the grid and load. Moreover, it can provide other services that any typical shunt-series compensation arrangement provides. Design and analysis of a single-phase CPAT is presented showing the effect of coupling between windings and transformer parameters affecting CPAT operation. In this paper, control of the CPAT in a Unified Power Quality Controller (UPQC) application is investigated to attenuate grid-current and load-voltage harmonics as well as compensate for reactive power requirements and mitigate grid inrush current. Through simulation and experimental implementation, the merits and performance of the CPAT were validated.

Index Terms—Power transformers, Magnetic circuits, Power conditioning, Power distribution

I. INTRODUCTION

One of the main challenges in the expansion of a power system is the issue of eliminating transmission and distribution system constraints and bottlenecks. With the increased peak customer demand, the distribution system suffers severe power quality and continuity of supply issues [1]. There is general consensus that the future power grid will need to be smart, fault tolerant, self-healing, dynamically controllable, and energy efficient [2]. Such requirements can be achieved through fast dynamic control provided through the installation of FACTS (Flexible AC Transmission Systems) and CPD (Custom Power Devices) which can cope with the trending changes in the power system [3]. With such devices playing an important role in the power system, it is essential to develop flexible integration capability into the distribution and transmission system.

Modern compensation devices utilize power converters connected in shunt and/or series to the electrical network to achieve the required compensation objective. Connection of

compensation devices can be achieved through transformers [4] or with a transformer-less approach [5]. Limitations in applicability of the transformer based approach is mainly due to the use of bulky and complicated zigzag transformers to achieve the required VA ratings and desired waveform. Meanwhile, non-isolated connection of these systems on the high-voltage (HV) side of the power system requires special complex converter structures which increase size and cost of installation. Converters installed on the low-voltage (LV) side incorporate high compensation currents increasing the size and cost of heat dissipation [5].

Considering the presence of coupling step-up and step-down transformers in the power system, it is beneficial to utilize the essential presence of these transformers while achieving the required coupling of FACTS devices and CPDs. Integrated magnetics have been investigated in the literature in the form of coupled inductors, integrated inductor and transformer, and integrated transformers (several transformers sharing a common core) [6]. Integrated transformers would present a benefit in terms of reduced number of magnetic components which in turn reduces the cost and volume of construction. Moreover, the ability to combine several transformers into one, would facilitate sub-transmission and distribution transformers with special functions of stability and quality improvements to the power system.

Integration of power electronics in transformers for such functions has been discussed in the literature and includes transformer core sharing [6], shunt integrated transformers [7], and controllable reactor [8]. These configurations have been utilized in FACTS and CPD applications in the form of series voltage compensation [9], shunt reactive power compensation [10], series harmonic passive filtering [11], series power flow control through controlled transformer saturation [12] and several other applications that involve series or shunt compensation. Another approach is to avoid the use of transformers and utilizing high-power back to back converters to increase controllability [13]. These approaches present limitation in terms of achieving one kind of compensation (series or shunt) and construction complexity.

Modification to a transformer winding configuration in order to incorporate series and shunt services has been

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discussed in the development of the “Sen” transformer (ST) [14]. Using tap changers to inject a compensation voltage, based on control parameters the ST can operate as a UPFC with certain degrees of freedom [15]. However, ST presents several limitations including use of tap changers which introduces certain limitations in the degrees of freedom, inability to provide extra services to the grid such as inertia emulation and fast dynamic control over power flow[16]. It is worth noting that no studies have discussed the integration of series and shunt compensation in sub-transmission and distribution level transformers which could provide a dynamically controllable transformer while considering minimization of size and cost of construction.

This paper presents a power electronics integrated transformer used in CPD applications. The CPAT can replace distribution transformers to provide services that will help maintain power system stability and reliability. The concept of CPAT relies on combining shunt and series windings to the structure of a transformer in order to incorporate the required services to the grid. Such services are achieved by controlling the currents and voltages in the auxiliary windings of a CPAT through passive or active techniques. In this paper, the application of CPAT in UPQC is investigated with a non-linear load and distorted grid voltage. Using a power electronics converter, active control of auxiliary windings current and voltage is achieved to attenuate grid-current and load-voltage harmonics, load reactive power requirements and grid inrush current to the transformer.

The paper is organized as follows: Section II presents the theory of operation of CPAT for a single-phase system and its magnetic circuit model. Section III shows the application of CPAT as a single phase UPQC with inrush current mitigation capability, Section IV presents simulation evaluation of the single-phase CPAT and Section V shows its equivalent experimental evaluation. Conclusions are summarized in Section VI.

II. CONCEPT OF CUSTOM POWER ACTIVE TRANSFORMER

A. Configuration

Based on magnetic circuits theory, windings wound over a common core are equivalent to shunt electrical circuits while windings wound over shunt cores are equivalent to series electrical circuits [6]. The construction of a single-phase transformer with auxiliary windings that are equivalent to shunt and series circuits is presented in Fig.1 which forms the basic concept of a single-phase CPAT. The configuration in Fig. 1 shows the structure of a single-phase CPAT with primary voltage v_{prim} , secondary voltage v_{sec} , shunt compensation current i_{sh} and series compensation voltage v_{ser} . In order to realize the theory of operation of the CPAT, an equivalent magnetic model of the structure is derived through the conventional modeling approach of magnetic circuits using electric circuit analogy [17]. However, the accuracy of the magnetic circuit is related to the assumptions made to transform the magnetic core into an equivalent magnetic circuit. Transformation of this magnetic structure to a magnetic circuit requires identification of magnetic paths to be represented by reluctances. Such procedure has been explained in [17] and [18].

The equivalent magnetic circuit in Fig. 2(a) represents the transformer in Fig. 1 with F as the induced magneto-motive force (mmf) from each winding, Φ as the flux in each limb and $\mathcal{R}$ as the equivalent magnetic reluctance in the transformer core and air. Subscripts *prim*, *sh*, *ser* and *sec* represent parameters of primary, shunt, series and secondary windings, respectively.

Due to the existence of non-linear characteristics in the iron core, a non-linear reactance is used to represent each iron limb and a linear reactance for leakage air path. Non-linear reluctances $\mathcal{R}_Y$ and $\mathcal{R}_L$ represent yoke and limb iron core modelled as an opposing mmf source following the B-H characteristics of the core material. Meanwhile, winding leakage reluctances $\mathcal{R}_{L_{prim}}$, $\mathcal{R}_{L_{sec}}$, $\mathcal{R}_{L_{sh}}$, $\mathcal{R}_{L_{ser}}$ and core leakage reluctance $\mathcal{R}_0$ are linear reluctances representing leakage flux through air. These reluctances are calculated based on limb length and cross-sectional area.

The magnetic circuit is affected by the applied voltage and currents in the winding electric circuit shown in Fig. 2(b). Each mmf source in Fig. 2(a) is coupled to a winding electric circuit in Fig. 2(b) consisting of winding resistance (R_w) and core-losses equivalent resistance (R_c). The effective voltage (v_e), is based on the effective flux (Φ_e) induced in the magnetic circuit and number of turns of the winding (N_w) as in (1). The mmf generated in the magnetic circuit is dependent on the effective current (i_e) in the electric circuit as in (2).

$$v_e = N_w \frac{d\Phi_e}{dt} \quad (1)$$

$$F_e = N_w i_e \quad (2)$$

Fig. 1. Configuration of a single-phase CPAT.

Fig. 2. Equivalent model of a single-phase CPAT (a) equivalent magnetic circuit and (b) winding and core-losses electric circuit.

Using Equation (1) and (2), the generated mmf by each winding (F_w) and fluxes in each limb (Φ_k) can be derived as shown in (3) and (4) where $\mathcal{R}_w$ is the leakage reluctance per winding. Using Ampere's and Gauss's laws, the coupling between winding voltage, current, fluxes and mmfs is derived in (5) and (6). Since mmfs and fluxes are affected by both voltage and current as shown in (3) and (4), to simplify the analysis, R_w is assumed minimal while R_c and $\mathcal{R}_w$ are assumed high. This assumption attenuates the effect of voltage on mmf and current on flux.

Equation (5) shows that the mmf on the secondary winding (F_{sec}) is a result of the sum of primary mmf (F_{prim}) and shunt mmf (F_{sh}). In UPQC applications, with a harmonic demanding load current as in (7) with n harmonic orders, the effect on the primary current can be attenuated by injecting harmonic currents in the shunt winding. However, with a non-ideal transformer, the difference between primary and secondary voltage harmonics combined with the non-linearity of core reluctances ($\mathcal{R}_L$, $\mathcal{R}_Y$), can introduce extra components in the current as shown in (5). Nevertheless, this effect can be considered minimal based on design consideration of the core. Moreover, these effects can be attenuated through the shunt winding as well when accompanied by an appropriate controller.

$$F_w = N_w \left(i_w \left(1 + \frac{R_w}{R_c} \right) - \frac{v_w}{R_c} \right) \quad (3)$$

$$\Phi_k = \frac{1}{N_w} \int (v_w - i_w R_w) dt - \frac{F_w}{\mathcal{R}_w} \quad (4)$$

$$F_{prim} + F_{sh} = F_{sec} + (\Phi_{prim} - \Phi_{sec})(\mathcal{R}_L + 2\mathcal{R}_Y) \quad (5)$$

$$\Phi_{prim} + \Phi_{ser} + \Phi_{sec} = \Phi_0 = \frac{F_{ser} - \Phi_{ser}\mathcal{R}_L}{\mathcal{R}_0} \quad (6)$$

$$v_w, i_w = \sum_{h=1}^n I_h V_h \sin(h\omega t + \theta_h) \quad (7)$$

The relationship between limb fluxes in (6) shows that the summation of all fluxes is equal to the core leakage flux (Φ_0). Considering flux is mainly affected by the voltage, harmonic voltages from the primary can be attenuated at the secondary through the applied voltage on the series winding. This performance is mainly affected by the core leakage reluctance ($\mathcal{R}_0$), a decrease in $\mathcal{R}_0$ would amplify the effect of $\mathcal{R}_L$ which is non-linear and would add up harmonic components on the secondary flux. However, $\mathcal{R}_0$ is typically low and with design considerations, core leakage can be minimized to achieve the required performance.

A decrease in $\mathcal{R}_w$ in (4), would require the shunt and series controllers to inject higher magnitude compensating current and voltage respectively due to the effect of the mmf on the fluxes in (5) and (6).

The coupling between the shunt and series winding can be realized in (5). As the series controller injects harmonic fluxes Φ_{ser} , the difference between Φ_{prim} and Φ_{sec} increases. Therefore, if the core reluctances are significant, the shunt winding would be required to compensate for harmonics present due to this difference too.

The presence of an equivalent shunt and series circuit from the configuration in Fig. 1 can be observed by transforming the magnetic circuit in Fig. 2 to a topologically correct equivalent electric circuit model through the principle of duality discussed

in [17]. The duality equivalent circuit shown in Fig. 3 is represented by the elements L as the equivalent inductance of each reluctance. It can be observed that v_{sh} is equivalent to a shunt circuit to the primary winding while v_{ser} is equivalent to a series circuit between the primary and secondary.

Extension of the single-phase CPAT to three-phase applications could be achieved by using three-single-phase CPATs where each CPAT represents a single-phase with series and shunt compensation. This is a suitable configuration when the three-phase CPAT is compared to a three-phase compensation system consisting of multiple single-phase transformers. Another approach is to stack all the three CPAT cores on top of each other as in a typical three-phase shell type transformer. The resulting structure would share common yokes between phases as well as reduce required number of tanks, bushings, protection equipment and footprint. Since the three-phase application is outside the scope of this paper, analysis and merits of such configurations are left for future publications.

Fig. 3. Equivalent electric circuit of a single-phase CPAT.

B. Characteristics

The main characteristics of CPAT as compared to the conventional multi-transformer approach (series and shunt compensators connected to the grid using separate insulation transformers with a distribution transformer in between) can be summarized into size reduction and facilitating services to the grid.

In a multi-transformer approach, two windings per phase and per transformer are required. Therefore, the total number of windings required in a single-phase system would be $6p$ where p is the number of phases. The CPAT requires $4p$ windings to achieve the same objective. Assuming the number of turns are identical, this yields a total number of windings reduction of 33%. Meanwhile, size of the resulting CPAT structure combines the three single-phase core type transformers into one, replacing two transformers with one central limb in the main transformer.

The CPAT enables utilization of a single transformer with controlled flux to provide services to the load, transformer and grid such as reduced inrush currents, harmonics elimination, voltage regulation, reactive power compensation and other grid supportive services based on the control technique.

As compared to the multi-transformer approach, the CPAT eliminates the requirement of high voltage/current handling windings usually present in the grid side of series and shunt isolation transformers that connects power electronic converters to the system.

The overall reduction in cost and the integration of power converter with transformer as a single unit makes it an attractive approach to minimize the requirement of several cascaded compensation systems.

III. APPLICATION OF CPAT

A. Configuration

In a distribution system, the single phase CPAT in Fig.1 can be combined with a three-phase converter adopted from [20] for UPQC application purposes as shown in Fig. 4. The objective of the shunt winding in the proposed UPQC is to achieve sinusoidal grid current, damp grid current during transients, compensate for reactive power requirements and maintain a constant DC bus voltage. The series winding would be required to achieve sinusoidal load voltage and regulate load voltage magnitude.

In Fig. 4, leg 'a' of the converter is connected to the series winding through an LC filter where the voltage across the capacitor is controlled in order to achieve the required series compensation voltage. Leg 'b' of the converter is connected to the shunt winding through an LCL filter where the filter output current is controlled according to the required shunt compensation. Design of the series filter inductor (L_a), shunt filter inductors (L_{b1} and L_{b2}), series capacitor (C_a) and shunt capacitor (C_b) are based on the required control bandwidth and the switching frequency of the converter. Passive damping of the LC and LCL resonance is accomplished through damping resistance R_a and R_b .

Leg 'c' is the common leg between both windings and represents the current return path of both phases. Having a common leg for both compensation presents a control challenge due to coupling between the converter legs. Among the strategies proposed in the literature to decouple the control of each leg, the strategy in [21] based on Three-Leg UPQC Space Vector Modulation (TL-UPQC SVM) is utilized due to its simplicity and effectiveness. The resulting gate signals $G_{a,c}$, $G_{b,c}$ and $G_{c,c}$ are used to control the converter switches.

Fig. 4. Configuration of single-phase CPAT for UPQC application.

Assuming a non-linear load connected at the secondary winding of the transformer, harmonic currents on the secondary winding arise. Since the secondary limb magnetic circuit is in parallel to the primary limb, both primary winding and shunt winding would handle a similar mmf waveform.

Injection of shunt compensation current adjusts the required mmf from the primary and hence changing the required primary current accordingly as in (5). With such an approach, harmonic components present in i_{sec} can be compensated by i_{sh} such that the resulting i_{prim} is harmonics free. Moreover, i_{sh} would be absorbing fundamental frequency current to charge DC bus v_{dc} , compensating the reactive power required by the primary winding and reducing the transient current required from the grid.

Considering v_{prim} consists of harmonic components, they can be attenuated from arriving at the secondary winding by varying v_{ser} such that the resulting Φ_{sec} is sinusoidal as in (6) and therefore the v_{sec} would be sinusoidal too. Moreover, the magnitude of the fundamental frequency of v_{sec} can be controlled by injecting the fundamental component in v_{ser} to compensate for voltage swells and sags from the primary.

B. Control

The control architecture presented in Figs. 5 and 6 consists of two part controllers; shunt and series compensation. Series compensation shown in Fig. 5 consists of two parts; magnitude of the secondary voltage V_{sec} is maintained constant at the reference value V_{sec}^* through a PI controller. The resulting command voltage is multiplied by the secondary voltage synchronizing signal $\sin(\omega t)_{sec}$ in order to achieve an in-phase compensation of the secondary voltage magnitude. Meanwhile secondary voltage harmonics are compensated through Resonant (R) controllers tuned to required compensating frequencies $n\omega$ where n represents the harmonic order and a reference secondary voltage harmonics $v_{sec,h}^*$ set to zero. Resonant controllers are utilized due to their high gain at selected frequencies and no phase shift or gain at other frequencies [22]. Therefore, the controller would generate a command voltage at the selected frequency which would attenuate the error. The resulting sum of command voltages from the PI and R controllers obtains the required injected voltage v_{ser} , which is the output voltage from leg 'a' with respect to leg 'c' in the single-phase setup in Fig. 4.

Fig. 5. Series compensation control loop of single-phase CPAT-UPQC.

Fig. 6. Shunt compensation control loop for single-phase CPAT-UPQC.

The shunt compensation controller in Fig. 6 consists of four controllers; two controllers control the fundamental component of primary current, one is used for compensation of harmonic components and a shunt winding current controller which achieves the required reference current from the previous

controllers. The DC bus voltage controller maintains a constant reference voltage v_{dc}^* across the converter capacitor by absorbing active power from the primary winding of the transformer. The PI controller determines the required capacitor charging current i_{prim_dc} . i_{prim_dc} is synchronized with the fundamental primary voltage $\sin(\omega t)_{prim}$ to acquire the reference primary current i_{prim}^* . i_{prim}^* and feedback primary current i_{prim} are passed on to a (Proportional Resonant) PR controller tuned at the fundamental frequency in order to obtain the required fundamental shunt compensation current $i_{sh_f}^*$. The reference current would maintain a constant DC bus voltage, zero-reactive power from the primary winding and would dampen the primary current during transients. Primary harmonic currents are compensated through R controllers with a reference $i_{prim_h}^*$ which is set to zero. This obtains the required shunt compensation harmonic currents $i_{sh_h}^*$. The combined compensation current i_{sh}^* is controlled through a PR controller to obtain the required converter shunt output voltage v_{sh} .

Primary frequency ω , synchronizing signal $\sin(\omega t)_{prim}$, secondary voltage magnitude V_{sec} and secondary voltage synchronizing signal $\sin(\omega t)_{sec}$ are obtained through a Double Second-Order Generalized Integrator Frequency Locked Loop (DSOGI-FLL).

IV. SIMULATION RESULTS

The configuration in Fig. 4 with parameters tabulated in Table I was simulated to examine the operation of CPAT under different scenarios. To investigate the effectiveness of series harmonic compensation, the primary voltage was generated through a combination of harmonic components 3rd, 5th, 7th and 9th with the proportions 25%, 12.5%, 6.25% and 3.13% of fundamental component respectively. Shunt harmonics compensation was investigated by connecting a non-linear load at the terminals of the secondary winding to withdraw non-linear, active and reactive current with the harmonic spectrum consisting of 3rd, 5th, 7th and 9th with the proportions 23%, 6.34%, 1.56% and 0.85% of fundamental component respectively. Meanwhile, secondary voltage magnitude control was examined by applying voltage disruption during operation. Primary current transient damping was investigated by suddenly applying voltage to the primary winding to observe the inrush current effect with and without compensation

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Simulation step time	1 μ sec
Transformer rated power per winding	15 kW
Turn ratio	1:1
System voltage	220V
Reference DC bus voltage	400V
Switching frequency	10kHz
Controller sampling frequency	10kHz
Dead time	3 μ sec
R_a, L_a	15 m Ω , 1.5 mH
R_{ca}, C_a	2 Ω , 40 μ F
R_{b1}, L_{b1}	60 m Ω , 6 mH
R_{b2}, L_{b2}	20 m Ω , 2 mH
R_{cb}, C_b	4.7 Ω , 5 μ F
C_{dc}	5 mF

A. Harmonics Attenuation, Voltage Regulation and Reactive Power Compensation

During a primary voltage sag of 50% illustrated in Fig. 7, the secondary voltage magnitude controller increases the fundamental frequency component of the injected series voltage v_{ser} to compensate for this drop. It should be noted that the secondary voltage harmonic contents changes as the transformer is loaded. This is typically due to the inductive action of the transformer under load acting as a filter reducing the harmonic contents of the secondary voltage. However, this yields a voltage drop to the load voltage and the presence of magnitude controller is essential. Based on the transformer design, such drop can be minimized by considering low core leakage impedance which yields a higher reluctance path of yokes and end limbs as discussed in Section II.

The effect of the sag can be observed on the power exchanged between the converter and the grid in Fig. 8 and Fig. 9. The shunt leg of the converter absorbs more active power to supply the series leg to supply the difference in the voltage. This can be also be observed in the DC bus voltage and current in Fig. 10. As the series leg demands more power, the DC bus voltage decreases until the shunt controller provides sufficient power to the DC bus.

Enabling the shunt harmonics controller results in the injected current shown in Fig. 11 which includes harmonic components required by the load. The series harmonics controller injects harmonic voltages into the series winding as illustrated in Fig. 12 to attenuate the secondary voltage harmonics. The resulting harmonic components present in the primary current were reduced to 0.05% and secondary voltage to 0.5% which shows the effectiveness of the CPAT in harmonics attenuation.

It should be noted that the series harmonics compensator not only compensates for harmonic voltages present in the primary, but also harmonic voltages induced due to the non-linear current absorbed by the load and passing through the transformer equivalent reluctance as in (6). Controller parameters and filters affect the bandwidth over which compensation is possible. Moreover, inverter output voltage and current harmonics will affect the resulting compensation.

Enabling the reactive power compensator, shunt reactive current was injected into the transformer eliminating the requirement of reactive power from the primary side as shown in Fig. 13. The required reactive power by the transformer is dependent on the transformer design and equivalent impedance.

B. Inrush Current Mitigation

The reactive power compensation controller presented in Fig. 6 can achieve damping of primary current during transients. Therefore, during transformer excitation, the required inrush current can be supplied through the shunt winding to the transformer and thus reducing its impact on the source grid. To simulate inrush current, effect of saturation was taken into consideration in the transformer model as in Section II with each limb reluctance represented by a controlled mmf source opposing flux direction based on BH curve characteristics. The inrush current through the transformer when rated primary voltage was applied with no load is shown in Fig. 14. The magnitude, harmonics and decay time of the

primary current shows the significant impact of the inrush current on the grid.

Enabling shunt compensation controllers would dampen the primary current magnitude during such transient. This is achieved through its reactive power compensation controller, which acts directly on the primary current magnitude at fundamental frequency. The reference primary current at startup is zero, since the DC bus is fully charged and thus the reactive power compensation controller would maintain a zero primary current at energization. Moreover, primary current harmonics are mitigated through the primary current harmonics controller. This can be observed in Fig. 15 where the primary current magnitude and harmonics are significantly minimized. However, the transformer still absorbs the same inrush current to energize through the primary and shunt windings.

Due to the high current passing through shunt winding in this compensation strategy, it should be noted that the simulation presented here is based on operating the converter at extreme conditions where current and applied voltage to the filter are operating beyond nominal rated values and below absolute maximum values. Moreover, the series winding may be shorted at start-up to avoid connection of the filter circuit to the series winding acting as a load. During this operation, DC bus control is disabled to avoid absorbing charging current at start-up through the shunt winding yielding a higher inrush current. Thus, this operation requires a pre-charged DC bus. Another issue which is not addressed in the presented controller is the decaying dc-offset shown in Fig. 14 and Fig. 15, as the inrush current tends to a steady-state.

A harmonic analysis of the inrush current in Fig.16 illustrates the capability of the shunt controller to mitigate fundamental and harmonic components throughout the inrush current cycles; this mitigates the peak current required from the grid during each cycle as in Fig.17. The performance of this mitigation is reliant on the controller and converter bandwidth. An average over 15 cycles shows a 51.5% reduction in the inrush current peak magnitude with the utilized setup.

Fig. 7. Voltage and current waveforms during 50% primary voltage sag.

Fig. 8. Active Power variation during a 50% primary voltage sag.

Fig. 9. Reactive Power variation during a 50% primary voltage sag.

Fig. 10. Converter DC voltage and current during 50% primary voltage sag.

Fig. 11. Voltage and current waveforms with shunt harmonics compensation.

Fig. 12. Voltage and current waveforms with series harmonic compensation.

Fig. 13. Voltage and current waveforms with reactive power compensation.

Fig. 14. Voltage and current waveforms during inrush transient without compensation.

Fig. 15. Voltage and current waveforms during inrush transient with compensation.

Fig. 16. Harmonic components of primary current during inrush transient without compensation (solid line) and with compensation (dashed line).

Fig. 17. Peak magnitude of primary current during inrush transient.

V. EXPERIMENTAL RESULTS

The hardware setup illustrated in Fig. 18(a) was implemented as shown in Fig. 18(b) consisting of a 50 kW three-phase core-type transformer of which four windings are used for primary, secondary, shunt compensation and series compensation. Primary voltage and compensating voltages are provided through a 21 kW (7 kW/phase) three-phase Power Amplifier to examine the effect of injecting voltage into the series and shunt winding. The three phases of the amplifier U, V and W are used such that phase U emulates primary voltage through the reference v_{prim}^* , phase V injects a controlled shunt compensating current through the reference v_{sh}^* and phase W applies series compensating voltage through the reference v_{ser}^* . v_{prim}^* is generated by OPAL-RT independent of the control algorithm with a defined harmonic spectrum. Control of the amplifier is achieved through an OPAL-RT real-time simulator which includes all the control structure for shunt and series compensation presented earlier in Fig. 5 and Fig. 6. The controller emulates the DC bus voltage by measuring the output current from the amplifier phases i_V and i_W which represent shunt and series compensation currents respectively. Data points of the results waveform have been captured for plotting and analysis.

A. Harmonics Attenuation, Voltage Regulation and Reactive Power Compensation

To investigate the effectiveness of the series compensation controller, a sustained 30% voltage sag was applied to the primary winding as shown in Fig. 19 at the instant indicated by the vertical line. With a reference of 195 V, it can be observed that the series controller injects an increased fundamental component to compensate for the voltage sag. The resulting voltage recovery during the sag is shown to be similar to the typical response of a dynamic voltage regulator.

Harmonic compensation was performed with a non-linear load connected at 200V operating voltage. Series harmonic compensation controller performance is shown in Fig. 20 as it was enabled at the instant indicated by the vertical line. It can be observed in Fig. 20 that the transformation of the secondary voltage from a harmonic-rich voltage to a sinusoidal voltage. As mentioned earlier, harmonic components present in the secondary voltage arise from primary voltage harmonics and

load current harmonics. This can be observed in Fig. 21, when a sinusoidal voltage was applied to the primary while the harmonics controller of the series winding was disabled and shunt winding was enabled. Enabling the shunt harmonics controller at the instant indicated by the vertical line in Fig. 21, shows an attenuation in the primary current harmonics. However, secondary voltage consisted of harmonic components induced by the secondary current as in (5).

Reactive power compensation through the shunt controller is observed through the phase shift of the primary current with respect to the primary voltage as in Fig. 22. The shunt controller injects reactive current to the shunt winding, eliminating the required reactive power from the primary side for feeding the load and transformer as shown in Fig.23. Meanwhile, Fig. 24 shows that active power was supplied through the primary and absorbed through the shunt winding to maintain a constant DC bus during this operation.

Fig. 18. Single-phase CPAT experiment (a) diagram and (b) setup.

Fig. 19. Experimental waveforms during a 30% voltage sag.

Fig. 20. Experimental waveforms with shunt-series harmonics compensation.

Fig. 21. Experimental voltage and current waveforms with shunt harmonic compensation.

Fig. 22. Experimental voltage and current waveforms with reactive power compensation.

Fig. 23. Experimental reactive power variation during reactive power controller activation.

Fig. 24. Experimental active power variation during reactive power controller activation.

B. Inrush Current Mitigation

Mitigation of inrush current effect on the grid through the shunt controller was investigated in the experimental setup by applying 60% of the rated transformer voltage at no-load to the primary winding. Fig. 25 shows the peak current magnitude, harmonic contents and transient decay, as in the simulation results discussed previously. As the shunt controller was enabled, Fig. 26 shows the significant reduction in peak current magnitude and harmonic contents of the inrush current.

Further analysis of the resulting primary current waveform before and after compensation is shown in Fig.27. A significant reduction in the harmonic components of the primary current can be observed which eventually resulted in a reduced peak grid current as shown in Fig.28. An average over 15 cycles shows a reduction of 22.3% in the inrush current from the primary winding.

Fig. 25. Experimental primary inrush current without shunt compensation.

Fig. 26. Experimental primary inrush current with shunt compensation.

Fig. 27. Experimental harmonic components of primary current during inrush transient without compensation (solid line) and with compensation (dashed line).

Fig. 28. Experimental peak magnitude of primary current during inrush transient.

VI. CONCLUSION

The Custom Power Active Transformer proposed in this paper has shown the ability to combine the possibility of series and shunt services in a single transformer. Simulation and experimental results of a single-phase CPAT-UPQC show the ability of the transformer to achieve compensation of primary current harmonics, reactive power, secondary voltage harmonics and secondary voltage magnitude. Moreover, shunt compensation achieved inrush current mitigation during energization of the transformer, reducing the effect of inrush current on the source grid.

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VIII. BIOGRAPHIES

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