J. Inst. Eng. India Ser. B (August 2020) 101(4):361–371
https://doi.org/10.1007/s40031-020-00462-9

ORIGINAL CONTRIBUTION

Evaluation of Controlled Switching of Transformer in the Presence of Large Capacitive Component

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Received: 24 July 2019 / Accepted: 24 June 2020 / Published online: 11 July 2020

Abstract Controlled switching is proven as best mitigation technique for reduction in current transient arises during transformer and capacitor switching. Ideal targets for transformer switching are gap voltage peak without considering residual flux, whereas capacitors are switched at minimum gap voltage. Transformer–capacitor combined topology is adopted in specific conditions based on operational and economical constraints.Such topology presents behavior of transformer and capacitor in the same circuit hence conventional strategies for energization and de-energization are not feasible. This paper evaluates the application of controlled switching for transformer connected with large capacitor bank connected with weak grid. With the application of proposed methodology, the high frequency inrush current has been reduced along with reduction in voltage depression and total harmonic distortion. In this way, application of controlled switching not only reduces inrush transients but also improves the power quality at the point of common connection. The technique has been validated with field tests and simulations and is found quite effective.

Keywords Controlled switching · Inrush current · Capacitor bank · Transformer energization · Voltage dip · THD

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Introduction

De-regulation of electric markets and penetration of considerable renewable energy into grid puts additional switching constraints on power equipments. Transformers are switched frequently for meeting the technical cum economic requirements and presents inrush transients with flow of high amount of asymmetric current. The frequent switching of transformer is done by circuit breaker whose performance is affected by harmful transients. The inrush current of transformer is mainly due to nonlinearity of flux-current relationship. Controlled switching technology is widely used to mitigate inrush current and results in increased equipment life with enhanced power quality.

During switching of capacitive components, high frequency inrush current may have distorted nature with zero missing for several power cycles; such zero missing phenomenon is of serious concern from protection point of view. The frequency of capacitor inrush current may reach several kHz ranges depending upon value of capacitance and inductance of configuration. Due to lower characteristic impedance of capacitors, back to back charging of capacitor bank shows inrush current up to 25–40 pu level. De-energization of capacitor bank at unfavorable instant also results in restrike in circuit breakers causing breaker contact degradation. During de-energization of long cables directly connected to transformers exhibits over-voltages and reached the switching over voltage (SOV) level of system [1]. Such situation may endanger the equipment and system from dielectric failure view point. There are certain cases where capacitors are directly installed to transformer. Therefore, energization and de-energization of transformer terminated capacitors are quite critical. Controlled switching is presently a matured technology for minimizing quantum of inrush currents generated during switching of power system equipment like transformers, capacitors and reactors with the application of intelligent electronic devices (IEDs) [2]. Circuit dynamics for inductive and capacitive components are different and hence different conditions arrive for switching these components with least transients. Controlled switching strategies for transformer may not be favorable for capacitor switching and best strategies for capacitor will not be optimum for transformer switching. Problem for evaluating optimum instant for L–C combination becomes more stringent when configuration has considerable inductance and capacitance [3, 4]. With the increase in rating is transformer, its inductance also increases resulting in considerable inrush effect during energization. Although power transformer has certain inherent capacitance associated with inter-winding and bushing, this capacitance is very less comparable to its inductance hence will not require any correction to default strategies. But with significant capacitance, default strategies for transformer and capacitor bank switching will not be effective for gaining desired results from independent pole switching. Ideal strategies for switching transformer–capacitor combination is to target instant for each phase such that resultant core flux remains symmetrical [5, 6]. Due to magnetic/electric coupling of windings, the dynamic flux induces even without charging of second phase. Also, charging of transformer with capacitor is the source of harmonics in current and voltage phasors; these may deteriorate the power quality of whole grid.

The presence of capacitive component in the vicinity of transformer creates high frequency currents with greater magnitude at transformer terminals during its energization. The configuration is analogous to transformer terminated line since long EHV transmission lines are source of capacitive reactance. The transformer core will be fully or partially de-magnetized when large capacitive component is directly connected to transformer. The energy stored in inductance of transformer will be fully compensated by the connected capacitance, and square wave pulses will be noticed at its terminals [7]. In normal cases, nearly 10% voltage remains coupled to transformer due to stray capacitance. However, energization targets would not need to alter for considering this small coupling voltage. Ideal energization instant for transformer is at peak of phase-neutral voltage wave if no residual flux is present. Charging instants for transformer in the presence of residual flux is when prospective flux equals residual flux [8].

Different strategies have been reported in the literature to minimize the inrush current generated during energization of transformer [9–12]. In weak grid conditions, sudden application of high-magnitude inrush current causes severe voltage dip in network voltage and adversely affects the power quality and may trip sensitive loads like HVDC converter systems and variable frequency drives. Effectiveness of each controlled switching methodology depends upon various factors like grid strength, rating of transformer, configuration, rate of decrease in dielectric strength (RDDS), statistical scatter and needs correction in targets to achieve desired results. Considerable work has also been done in field of controlled switching of capacitor bank [13]. Overvoltages generated during de-energization of capacitor bank and cable systems are also addressed in the existing literature [14]. Problems encountered during charging transformer terminated line are analyzed by [1]. Moreover, CIGRE (A3) has also presented detailed analysis of controlled switching strategies for transformer and capacitor bank. But there is no such literature available explaining optimum energization instant for case where transformer is directly connected to capacitor.

This paper presents controlled switching strategies for energization and de-energization of coupled three winding power transformer with capacitor bank on its tertiary side. The results are verified by simulation as well as field cases. Power quality of system is analyzed from THD/voltage dip view point for both current and voltage phasors. Analysis of voltage dip with and without application of controlled switching strategies is also analyzed in this paper.

Effect of Capacitance on Controlled Switching of Transformer

Capacitive component has inherent capacitive reactance thus causing switching surge during its switching [15]. Inrush current generated during capacitor energization is a direct function of voltage change at the moment and accordingly they offer least inrush during charging at voltage zero. As reported in the literature, reactors are used to compensate capacitive reactance with inductive reactance offered by reactors [3]. Similarly, in case of transformer terminated capacitor/line, capacitance is counterbalanced by inductance of transformer resulting in predominant de-magnetization of transformer core post its de-energization, and this is added advantage with this configuration [16]. But during charging of transformer–capacitor combination situation becomes tricky, because default strategies for transformer or capacitor switching will not be effective in this combination. During charging of L–C circuit, inductance of transformer will interact with capacitance, and ferro-resonance condition may occurs several times accompanied with flow of large amount of current with over voltages at transformer terminals. During these conditions, current is only limited by resistive component of circuit impedance. Hence, energization of L–C circuit needs careful selection of energization instant even with controlled switching. Figure 1 shows circuit diagram of L–C combination representing transformer with

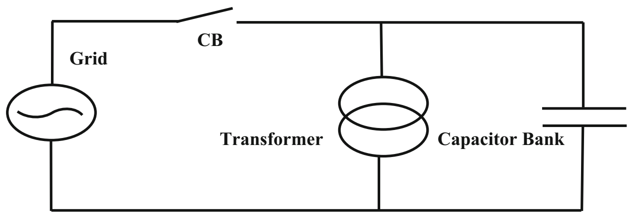

Fig. 1 Circuit diagram for analyzing charging current in L–C combination

capacitor bank directly connected, and single circuit breaker is installed to switch on/off the combination.

The current during energization of capacitor coupled transformer [5] is given by Eq. (1):

$$I = I_m \frac{\beta}{\sqrt{LC}} e^{-\alpha t} \left\{ \begin{array}{l} \sin(\theta_0 - \emptyset)\sin(\beta t - \gamma) \\ -\frac{1}{\omega\sqrt{LC}}\cos(\theta_0 - \emptyset)\sin \beta t \end{array} \right\} + I_m \sin(\omega t + \theta_0 - \emptyset) \quad (1)$$

where

$$\alpha = \frac{R}{2L} \quad \beta = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$$

$$\gamma = \tan^{-1}\frac{\alpha}{\beta} \quad \emptyset = \tan^{-1}\frac{\omega L - \frac{1}{\omega C}}{R}$$

Θ_0 is the energization angle; ω is the angular power–frequency; L is the inductance of transformer; C is the capacitance of filter bank; I_m is the peak inrush current; R is the resistance of circuit; Ø is the circuit power factor angle; α is the time constant of circuit ($R/2L$).

As per Eq. (1), charging current contain sinusoidal steady-state current which is limited by impedance of circuit; beside sinusoidal current there is exponentially decaying asymmetric current having very high amplitude and this current decays with time constant of circuit. When circuit is charged at instant, energization angle equals to power factor angle $\theta_0 = \varnothing$, first part of exponentially decaying current will be omitted but transients are still available.

When circuit is energized at voltage peak ($\theta_0 = 90°$), maximum peak current will be observed, because power factor angle will be close to 90° electrical for purely capacitive circuit. Transients generated in circuit will be damped with time constant $R/2L$. Its magnitude is given by Eq. (2):

$$i = -I_m \frac{\beta}{\omega \cdot LC} e^{-\alpha t} \sin \beta t + I_m \sin \omega t \quad (2)$$

Switching at voltage zero ($\theta_0 = 0°$) poses inrush phenomena of transformer, and again high-magnitude current will flow in transformer–capacitor circuit. Following three scenarios will be observed:

1. *Switching at voltage zero* ($\theta_0 = 0°$) Resulting in inrush current of transformer. Unfavorable position for transformer switching but suitable for capacitor energization. High-magnitude inrush current flowing with asymmetric component.
2. *Switching at voltage peak* ($\theta_0 = 90°$) Resulting in high frequency current transients due to capacitor switching at unfavorable position. Although it is suitable instant for transformer charging.
3. *Switching in between* ($\theta_0 = 0°–90°$) Compromise solution can be achieved by shifting the energization instant from voltage peak depending upon capacitance effect.

Therefore, switching of L–C circuit at both zero and peak voltage instant of phase-earth wave of respective phase offers switching transients. For finding the suitable voltage energization point, a trade-off is to be made in zone zero to peak of phase to neutral voltage.

Transformer energization at voltage zero shows worst condition and highest inrush currents with distortion are observed. Simulation study for determining energization instant for L–C combination is done in "Simulation study of transformer terminated capacitor" section.

Simulation Study of Transformer Terminated Capacitor

Proposed controlled switching strategies have been modeled in PSCAD software. Three winding transformer of configuration Yyd with rating 210MVA has been considered for simulation study. This configuration presents magnetic coupling, and therefore after charging of first phase, flux will be created in second and third phase with half magnitude of first. Saturation characteristic of transformer is enabled in simulation to accurately study the results. Timed independent pole circuit breakers are connected to switch L–C combination. The simulation studies are carried out considering nil residual flux. All the components are connected as per Fig. 2. High voltage winding of transformer is connected to constant voltage source; intermediate voltage winding is not connected to any load and is kept open. Capacitor bank is installed on tertiary

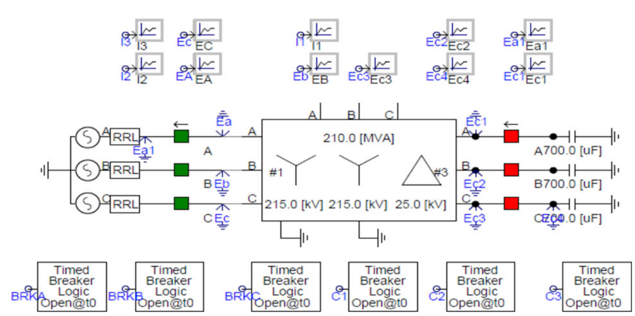

Fig. 2 PSCAD circuit arrangement for simulation study

winding of transformer and its magnitude is varied to study said effect at different capacitance values. Simulation set-up is constructed for 60 Hz system [17].

Transformer Energization

Ideal switching instant for transformer is at voltage peak while capacitor bank are switched at voltage zero of phase-neutral peak. In transformer terminated capacitance, minimum inrush can be achieved in between span. Targets are adjusted optimally in between 0° and 90° electrical of voltage wave. For smaller capacitance, lesser adjustment can results in better trade-off. Larger capacitance needs more correction from voltage peak and targets will be shifted more toward voltage zero during transformer energization.

In first case, transformer circuit is switched at voltage peak of phase-earth voltage wave resulting in considerable current transients due to the presence of capacitor in same circuit. The inrush current resulting during energization is tabulated for different capacitance values. Then, capacitance is increased in steps, and inrush current are tabulated for each step. This table states that inrush currents are increased with higher capacitance even for voltage peak switching. Energization waveform of transformer with capacitor bank results in high frequency transients with distortions as shown in Fig. 3. Without inclusion of capacitor bank, distortions are removed during energization and same is plotted in Fig. 4.

Table 1 indicates deviation in transient mitigation on closing target from voltage peak. Tests were conducted considering voltage zero energization instant with nil residual flux. Table 1 mentions inrush currents for different capacitance values for voltage zero and peak energization. However, these current also contains harmonics and distortions due to capacitance effect. The targets are then modified considering capacitance connected to transformer. It is found that ideal target for energizing this configuration is certain degree prior to peak. The resulting inrush currents after modified targets are reduced as

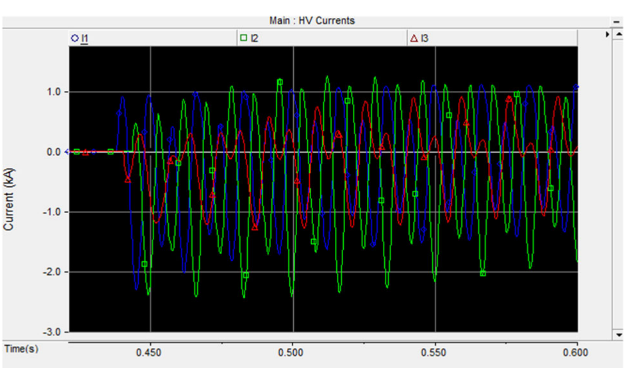

Fig. 3 Charging currents of L–C combination

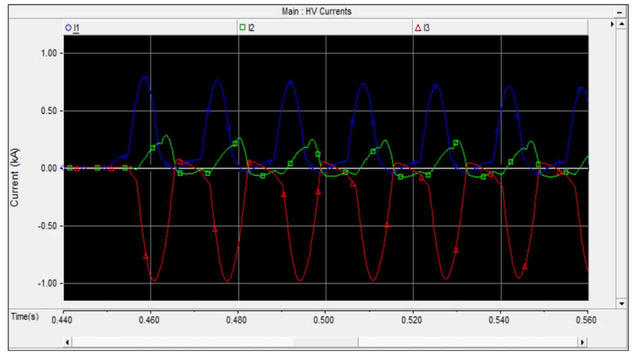

Fig. 4 Charging currents without filter bank

compared to previous case. After applying proposed strategy and trade-off, inrush currents are mitigated considerably as indicated in Table 1. Currents indicated in table are expressed in per unit (kA).

Table 2 indicates trade-off achieved for achieving minimum inrush current. This table indicates electrical degree deviation from voltage peak, which is optimum point for charging of LC combination. Timing energization sequence for energization of L–C combination is mentioned in Table 3 for different capacitance. Selected 60 Hz system has 1st phase voltage peak observed at 412 ms. Energization instant of first phase has predominant effect on inrush generation.

Transformer De-energization

Apart from energization complications, de-energization of transformer–capacitor is also a complex situation to be dealt carefully to avoid switching over voltages. Furthermore, the presence of capacitor bank causes its core de-magnetization. Square wave pulses will be seen during de-energization of transformer terminated with considerable capacitance. Complete damping of these square wave pulses requires considerable time to completely de-magnetize the core depending upon quantum of connected inductance and capacitance. For minimizing the switching transients, controlled de-energization is done in simulation study. Figure 5 shows the presence of square wave pulses during de-energization of transformer–capacitor combination with 600 μF capacitor bank. De-magnetization process restricts the energization of transformer due to the presence of residual charges.

Field Tests of Suggested Methodology

Field tests are carried out to verify the effectiveness of proposed methodology on three winding transformer having capacitor bank installed on its tertiary for reactive

Table 1 Reduction in inrush current for different capacitances using suggested methodology

Capacitance (μF)	Inrush current (kA) at 90° charging	Inrush current (kA) at 0° charging	Inrush current (kA) after trade-off
100	0.90	2.77	0.82
200	1.36	2.72	1.29
300	1.82	2.43	1.51
400	2.16	2.17	1.86
500	2.63	2.44	1.99
600	3.00	2.42	2.03
700	3.33	3.03	2.39

Table 2 Trade-off angle and deviation of electrical targets from voltage peak for managing minimum inrush

Capacitance (μF)	Difference from peak (elect. degree)	Trade-off angle (elect. degree)
100	19.44	70.56
200	21.38	68.62
300	32.40	57.60
400	36.72	53.28
500	41.04	48.96
600	49.68	40.32
700	56.16	33.84
800	65.64	24.36

Table 3 Energization sequence for optimal energization of L–C circuit

Capacitance (μF)	1st phase target (ms)	2nd phase target (ms)	3rd phase target (ms)
100	41,170	4165	4165
200	41,161	4165	4165
300	4111	4165	4165
400	4109	4165	4165
500	4107	4165	4165
600	4103	4163	4163
700	4100	4165	4165
800	4095	4165	4165

power requirements as shown in Fig. 6. The circuit shown in Fig. 6 belongs to utility operated on 60 Hz frequency having weak system strength. High voltage side of transformer is connected to bus bar through SF6 circuit breaker and isolator is provided at tertiary side to isolate capacitor bank. Voltage/current measurement facility (VT) is available at tertiary side to monitor current transients during switching of circuit.

This transformer has one winding connected in delta hence offer interphase coupling. Also, in this specific configuration only disconnector is provided for isolating the capacitor bank after de-energizing the transformer for maintenance/shut-down purpose, and no breaker is provided to isolate capacitor bank. Switching operations are carried out on HV side to minimize starting currents. Circuit breaker installed for switching the HV side is equipped with Controlled Switching Device (CSD). This circuit breaker is of SF6 type very low restrike probability and has good operating accuracy [18] and is suitable for application of controlled switching.

Transformer Energization

With filter bank Initially switching operation is done by keeping capacitor bank in circuit and HV side circuit breaker is closed. All phases are closed simultaneously and

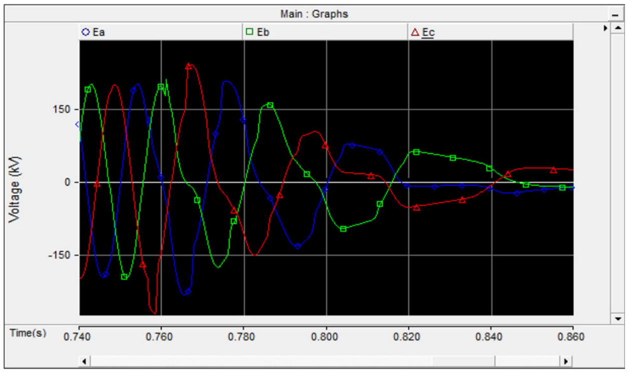

Fig. 5 Controlled de-energization of L–C combination having square wave pulses leads to core de-magnetization

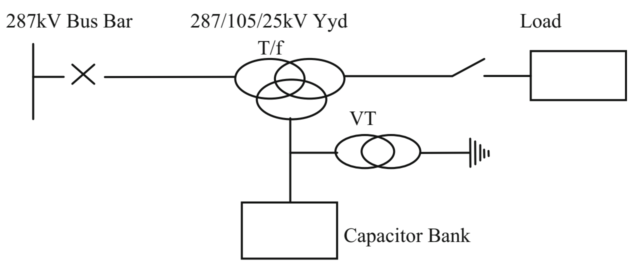

Fig. 6 Network diagram indicating filter bank directly connected on tertiary of the transformer

considerable inrush current is observed during energization. Peak inrush currents during random closing are shown in Fig. 7. Waveforms for all three phase currents and voltage recorded in disturbance recorder are shown in Fig. 8. As shown in figure, considerable harmonics in voltage waveform resulting in distorted waveform leading to reduced power quality. Upon sudden application of inrush current, considerable voltage dip and harmonic contents observed on bus bar voltage for certain time. Without application of suggested methodology, inrush currents up to 3 pu are observed which can adversely affect the life of system.

In next stage, controlled switching is applied and energization targets are modified with matching capacitance, deviated from voltage peak. During coarse tuning of targets, currents are reduced from maximum of 1818–414 A. In L-C combination, capacitor connected to tertiary is serving as load of nearly 198A, therefore the application of suggested targets holds the charging current near to loading of capacitor. During the fine tuning of controller, 1st phase is charged at 72° electrical from zero crossing of phase-neutral voltage wave and 2nd/3rd phase at 162°. The resulting inrush currents are considerably reduced and currents will be more sinusoidal. The reduced inrush currents are well below no-load rated current to the tune of 38-61A for different phases. Table 4 summarizes the inrush mitigation for different switching angles. Graphical representation of improvement of inrush current with and without suggested methodology is drawn in Fig. 9. Figure 10 shows current and voltage waveform extracted from disturbance recorder with application of controlled switching in conjunction with suggested methodology.

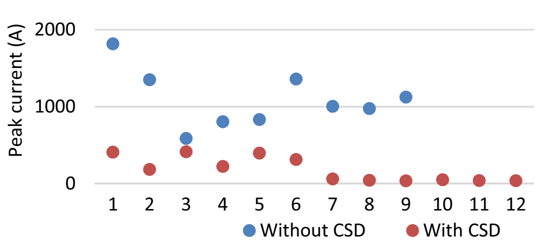

Fig. 7 Peak inrush current of transformer energization with and without filter bank

Without filter bank In next step, field tests are continued by disconnecting filter bank from circuit shown in Fig. 6. Without considerable capacitance in circuit, the charging of transformer poses lower inrush current as compared to previous case. Maximum inrush current of 1478A observed during charging considering targets far away from suggested time (ms) method. By applying the suggested methodology, inrush currents reduced to nearly no-load current values.

Minimum charging current of 12A observed after fine tuning of controller. Mitigated inrush current achieved by applying suggested methodology tabulated in Table 4. The consistency in achieving minimum currents is well within the statistical variation of SF6 circuit breaker as per IEC 62271-100.

Analysis of Voltage Dip

With the sudden application of large inrush current and depending on grid strength, voltage dip occurs across transformer HV terminal. During random charging of transformer with/without capacitor bank shows considerable voltage drop at bus bar and is undesirable from power quality view point. Table 5 shows voltage dips for different conditions during energization of transformer. Voltage dip of about 15% observed when transformer is charged away from desired targets. Thereafter, with fine tuning of targets voltage dip considerably reduced to nominal voltage. Distortions on voltage wave are also reduced owing to increased power quality. Figure 11 shows currents waveforms after applying controlled switching. Bus voltage during energization of LC combination using controlled switching shows lesser voltage dip and led to increased power quality; waveforms of bus voltage and phase currents are shown in Fig. 11. Graphical representation of improvement of voltage dip is shown at Fig. 12.

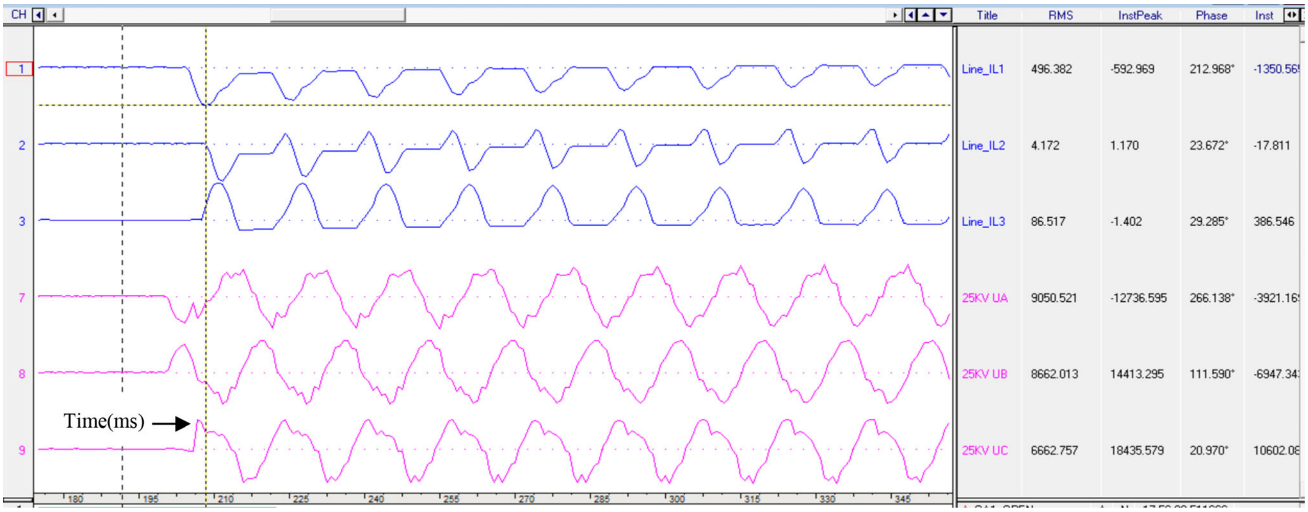

Fig. 8 Inrush current generation without application of controlled switching for LC combination

Table 4 Inrush current comparison with and without application of controlled switching

Target angle (°) from R–N voltage zero			Peak current (A)		
θ_R	θ_Y	θ_B	I_R	I_Y	I_B
With filter					
126	252	252	1818	805	1005
0	90	90	1350	833	977
72	270	270	587	1360	1125
72	198	198	396	184	409
72	180	180	313	414	223
Without filter					
90	145	145	717	400	343
72	145	145	900	545	1478
72	180	180	151	61	63
72	180	180	98	50	52
72	162	162	61	46	46
54	162	162	16	13	15
54	162	162	15	14	12

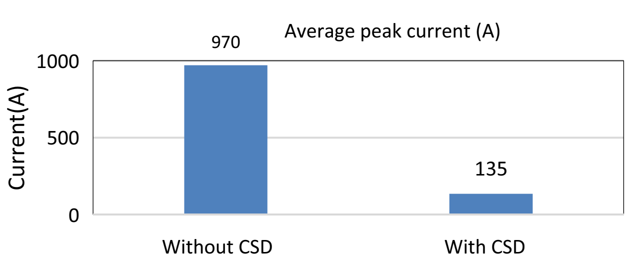

Fig. 9 Comparison of average inrush with different methods

Analysis of Total Harmonic Distortions

Energization of transformer alone or along with capacitor at unfavorable instant creates inrush accompanied with flow of lower order current harmonics and voltage dip. The presence of harmonics in voltage phasor reduces the power quality of grid and circuit both. Capacitors are the rich sources of harmonic injection in the system. Total harmonic content of voltage phasor without application of

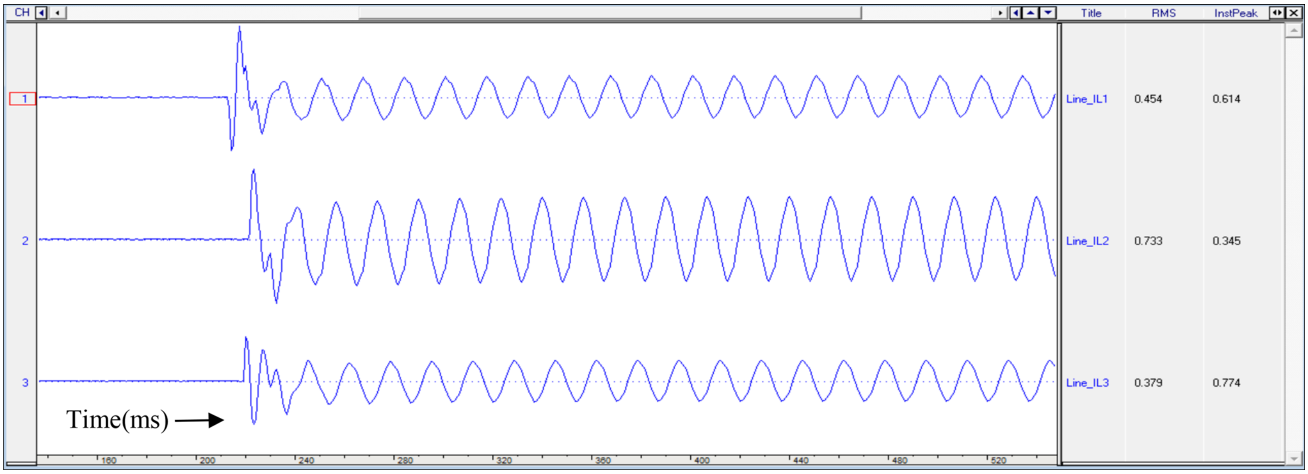

Fig. 10 Inrush currents with application of suggested methodology in the presence of filter bank

Table 5 Voltage dip comparison for different conditions

Inrush current (A)			Voltage dip (%)		
I_R	I_Y	I_B	Δ_R	Δ_Y	Δ_B
With filter					
1818	805	1005	− 10.88	− 14.94	− 11.25
1350	833	977	− 3.17	− 17.61	− 9.25
587	1360	1125	− 9.21	− 4.61	− 5.11
396	184	409	− 0.59	− 0.72	− 0.79
313	414	223	− 0.44	− 0.11	− 0.45
Without filter					
717	400	343	− 4.73	− 0.54	− 5.77
900	545	1478	− 18.67	− 8.31	− 0.55
151	61	63	− 0.08	− 2.64	− 1.52
98	50	52	− 1.49	+ 0.02	− 1.68
61	46	46	− 0.40	0.00	− 0.88
16	13	15	0.00	− 0.21	0.00
15	14	12	− 0.19	− 0.27	− 0.14

suggested methodology in the presence of capacitor found to about 23%. After fine tuning of suggested methodology, harmonic contents are considerably reduced to 2–12%. Comparative view of THD with and without application of CSD is indicated in Table 6 and harmonics are greatly reduced with the application of controlled switching.

Figure 13 indicates the total harmonic summary of voltage waveform as shown in Fig. 14 of a real transformer energization without application of suggested methodology. In absence of large capacitive component, harmonic content in voltage phasor further reduced to 0.7% level with the application of suggested method of energization targets. Figure 15 shows graphical representation of improvement in harmonic distortion in the presence of large capacitive component. Figure 15 indicates THD evaluated from disturbance records without correcting energization targets having higher THD.

Controlled De-energization of Transformer

De-energization of transformer with capacitor bank is also performed with controlled switching to minimize switching transients. R-phase is de-energized first at voltage peak following by de-energization of B and Y phase.

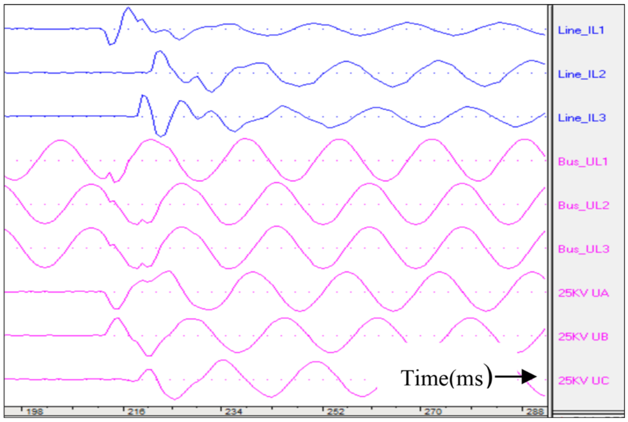

Fig. 11 Improvement in bus bar voltage dip with controlled switching

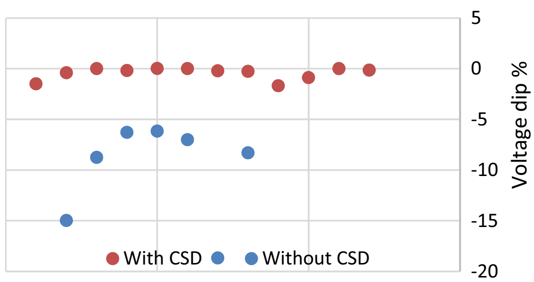

Fig. 12 Improvement in voltage dip with controlled switching

Energization and de-energization sequence is RBY to avoid flow of zero sequence. Figure 16 shows disturbance recorder waveforms during de-energization and displays de-energization of core. Controlled de-energization of L–C circuit helps in reducing switching over voltages occurred in network. Controlled de-energization not only improves power quality at bus bar but also mitigates chances of restrike at circuit breaker main contacts.

Limitations

Main scope of this work includes reduction in inrush current along with improvement in voltage dip occurred due to transformer–capacitor charging with the application of controlled switching. Since, capacitors are the main sources of harmonics, their interaction with inductance causes considerable harmonic content in current and voltage phasors. Although voltage harmonics has been significantly reduced, current harmonics are still present. Due to the presence of higher order frequencies upon charging of L–C combination considerable harmonics still presents. These harmonics can be further reduced with use of modern generation FACTS devices. Further, the study can be extended to 50 Hz frequency system.

Conclusion

Switching of transformer with considerable capacitance is non-conventional scenario, and hence existing charging strategies will not be effective. Controlled charging methodology has been proposed and validated in this paper

Table 6 Variation of harmonic distortion for different conditions

Peak inrush current (A)			Voltage harmonic distortion (%)		
I_R	I_Y	I_B	THD_R	THD_Y	THD_B
With filter					
1818	805	1005	11.07	10.69	11.34
587	1360	1125	21.29	22.62	22.51
1350	833	977	20.57	22.94	23.15
396	184	409	12.78	15.11	15.21
313	414	223	11.95	12.11	13.56
Without filter					
900	545	1478	22.34	22.67	18.91
717	400	343	14.11	17.54	15.99
151	61	63	6.22	3.51	3.17
98	50	52	6.11	3.57	3.69
61	46	46	3.81	2.71	2.54
16	13	15	0.69	0.71	0.68
15	14	12	0.71	0.81	0.83

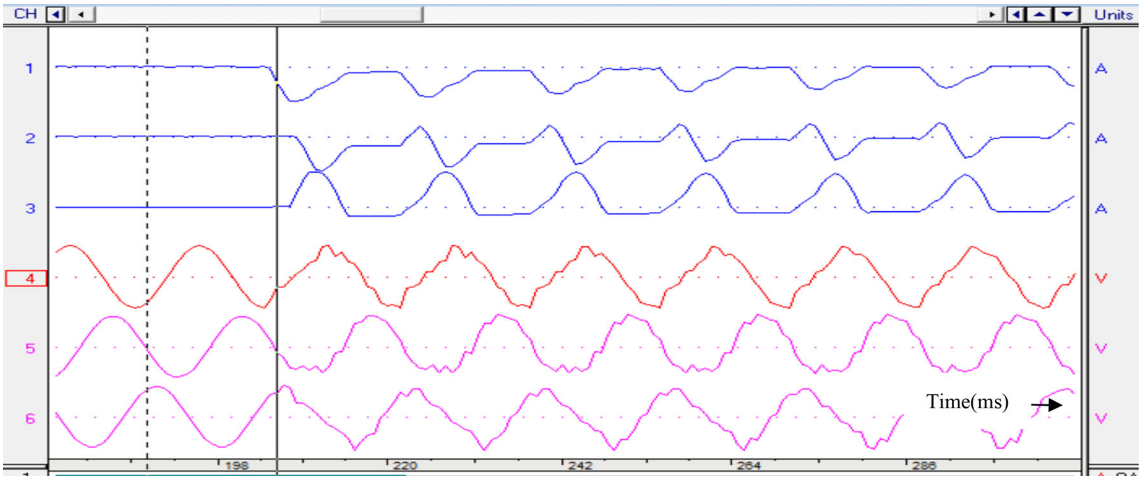

Fig. 13 Voltage waveform of transformer charging having significant harmonic content

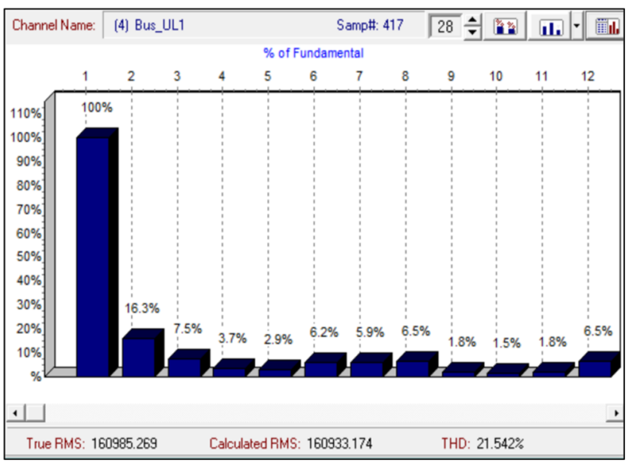

Fig. 14 THD of voltage phasor for L–C charging without modifying CSD targets

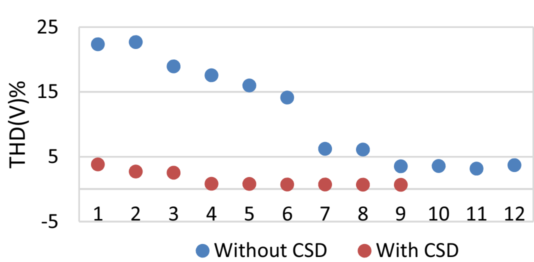

Fig. 15 Improvement of power quality after modification of phase energization targets

for switching of L–C combination in constrained weak grid environment. From the energization results, it is appreciated that high frequency inrush currents are considerably reduced along with reduction in voltage dip in network voltage. Moreover, total harmonic distortion during uncontrolled charging of L–C combination is very high and

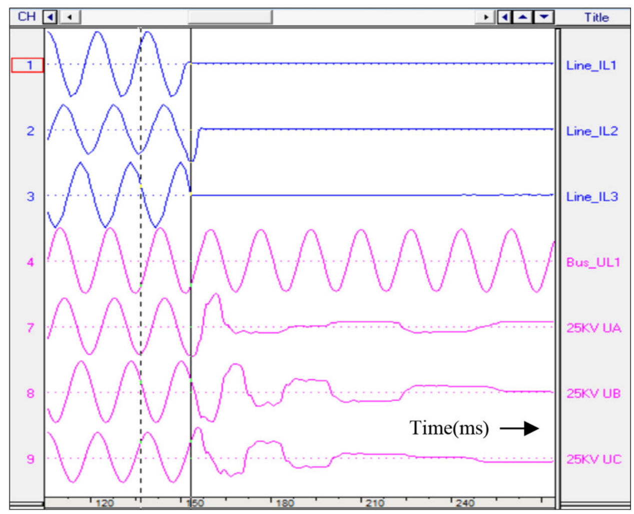

Fig. 16 Controlled de-energization of LC combination having considerable de-magnetization

has also been reduced to satisfactory level with the aid of controlled switching methodology.

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