

# Investigation and Reduction of Effects of Transient Signals for Switching Capacitor into a Power System by Using an Experimental Test Set

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**Abstract.** This paper aims to investigate switching capacitor bank of the 115 kV Nong Chok substation under the Electricity Generating Authority of Thailand (EGAT). The substation comprises of 3 steps capacitor banks with reactive power of 48 Mvar in each step. In case study, the substation is downscaled to be an experimental unit with 415 V and 5 Mvar in each step in laboratory. Inrush currents, the behavior of transient signals, that occurs when capacitors are switched into the system are studied and analyzed. To reduce the effect of switching capacitors, current limiting reactors connected in series with the capacitors are proposed. In addition, a zero-crossing circuit is designed to control switching angle of the capacitors, since it has a significant effect on the inrush currents. The results of experiment are compared with two case studies: switching capacitors without integrated 7% of reactors and switching capacitors with integrated 7%. It can be summarized that the switching capacitor without integrated reactors has inrush currents change based on the switched angles of the capacitors. However, the switching capacitor with integrated reactors gives inrush current values are almost approximate in each angles of switching and they are lower the case of the switching capacitor without integrated reactors. Nevertheless, reactor integration into the system leads to high current values at the steady states.

**Keywords:** Capacitor bank · Inrush current · Reactor · Switching

## 1 Introduction

Nowadays, we need to consume a lot of electrical energy for daily activity but some of the power systems, distributing and transmitting the electrical energy to the consumers, have unsuitable power factors resulting in low efficiency. Thus, a capacitor bank is one of the systems used to enhance the power system efficiency. Many research articles present that capacitor bank installation to an electrical system provides many benefits, for instance power factor correction, voltage support, reduction of harmonic distortion effect in transmission systems and increase of active power transfer capacity [1–3].

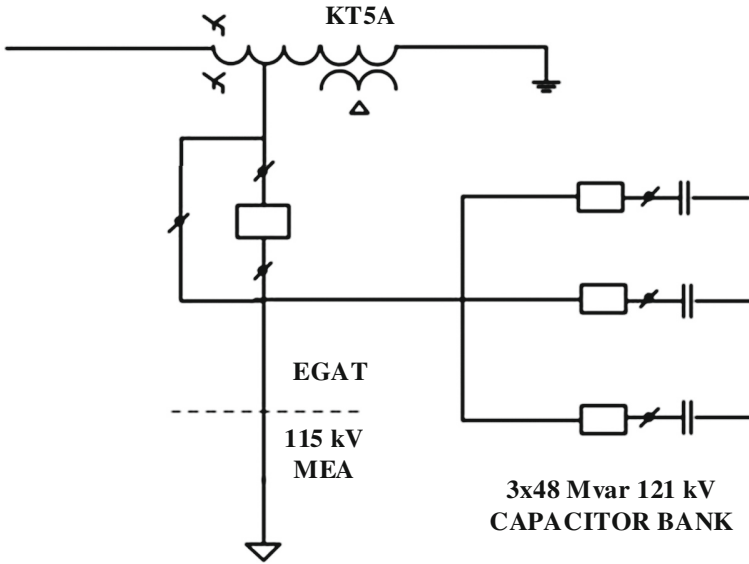
The investigation of efficiency improvement of power systems by integrating different types of capacitor bank units is presented in K. Tilakul [4] and C. Rivera [5] works. A capacitor bank comprises of capacitor units connected in series and parallel inside an enclosed bank. However, capacitor bank switching has a negative effect on power system operation which is inrush currents, overvoltage transience and harmonic problems, hence electrical equipment damage.

The inrush current from switching can be very high during short periods, which leads to the failure of electrical equipment operation. To limit the inrush current, J. C. Das [6] and Mirza Softić [7] present a power factor controller. Thyristors are used to control the power factor of the capacitor banks that are connected in series. Results indicate that this technique is effective and reliable. The installation of an electromagnetic relay with solid-state transient limiter into a capacitor bank is proposed [8–10]. There are two operation modes by using a thyristor to address any transient overvoltage and inrush current problems: limiting mode and bypass mode, which have a very simple structure and reliable performance [8]. Due to an increased voltage stress of a thyristor switch, paper [9] uses IGBT to turn-on and turn-off a switch without an inrush current at the voltage zero-crossing. IEEE Std C37 [11] proposes guidelines for shunt power capacitor bank and filter capacitor bank protection, aiming for many shunt capacitor installations and designs. Software simulation is used to investigate inrush current for single and back-to-back capacitor banks, revealing that the pre-insertion resistor technique can significantly reduce transient [12].

In this paper, switching capacitor bank of the 115 kV Nong Chok substation under the Electricity Generating Authority of Thailand (EGAT) is studied. The substation is downscaled to be an experimental unit in laboratory to study and analyze inrush currents. After that, current limiting reactors connected in series with the capacitors are installed to reduce the effect of switching capacitors.

## 2 Experimental Setup

The experimental model is set to simulate the 115 kV Nong Chok substation under the Electricity Generating Authority of Thailand (EGAT). A single line diagram of the capacitor bank system is shown in Fig. 1. The substation comprises of 3 steps capacitor banks with reactive power of 48 MVar in each step. The experimental test set is downscaled from 115 kV to 415 V in laboratory. In addition, the size of capacitors and other equipment is determined by using per unit calculation. Hence, the total capacity power is 15 MVar, 5 MVar in each step, with ungrounded wye for internal connection.

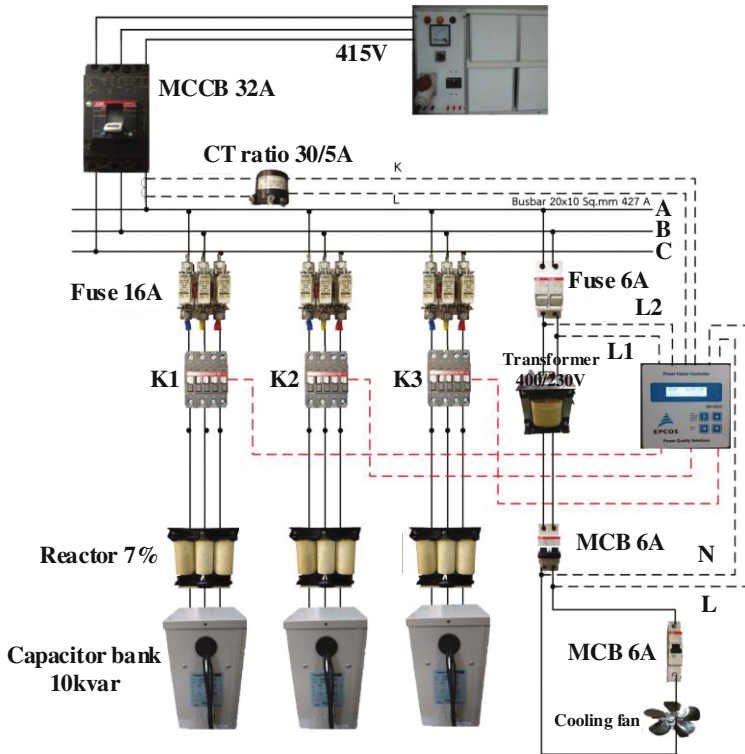


**Fig. 1.** The single line diagram of the capacitor bank system in the Nong Chok substation

The experimental setup receives a voltage of 415 V from a variable voltage transformer used to step up the voltage of the power supply in the laboratory. The voltage and current measured at phase A by a power factor controller are evaluated and processed, after that it sends a signal to the switching capacitors with the magnetic contactors K1, K2, and K3. The operation of the experimental test set is divided into two parts: a power circuit and a control circuit.

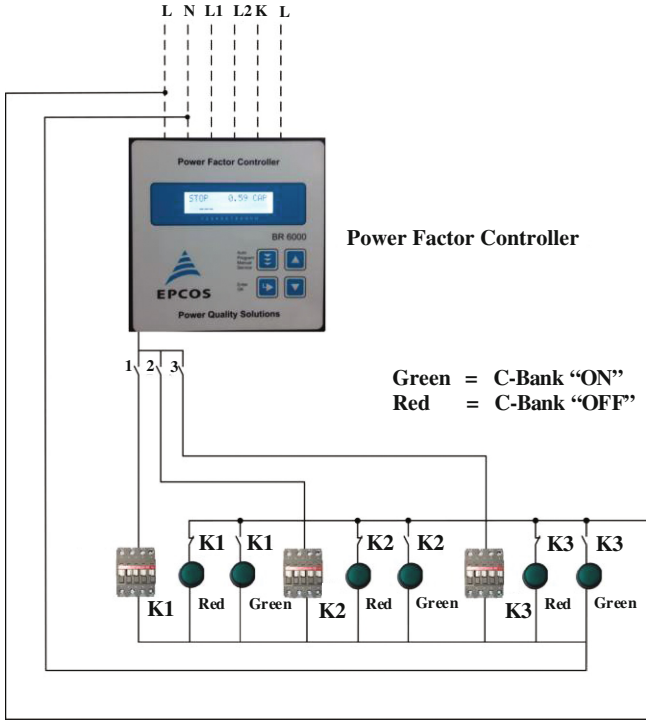
Figure 2(a) shows a schematic diagram of the power circuit of the experimental test set. The busbars of the power circuit receive a 3-phase voltage of 415 V three phase via a main circuit breaker. There are two main circuits connected with them. Firstly, the 415-line voltage of phase A is changed to 230 V by a step down voltage transformer in order to supply the control circuit (power factor controller) and a thermal ventilation system (a cooling fan). Next, the switching of the capacitor bank in each step consists of a HRC fuse, a magnetic contactor, a 7% reactor and a capacitor.

A schematic diagram of the control circuit of the capacitor bank system in the experimental test set is shown in Fig. 2(b) The control system comprises the power factor controller used to control the switching capacitor in each step. The power factor controller obtains current and voltage values from the current transformer (CT) and potential transformer (PT). The power factor of the system is calculated from these values to compare with the power factor value set inside the program. After that, the capacitor in each step is closed or opened with the magnetic contactor by using on/off signals from the power factor controller.



(a) a schematic diagram of the power circuit of the experimental test set

**Fig. 2.** The operation of the experimental test set (a) a schematic diagram of the power circuit of the experimental test set (b) a schematic diagram of the control circuit of the capacitor bank system



(b) a schematic diagram of the control circuit of the capacitor bank system

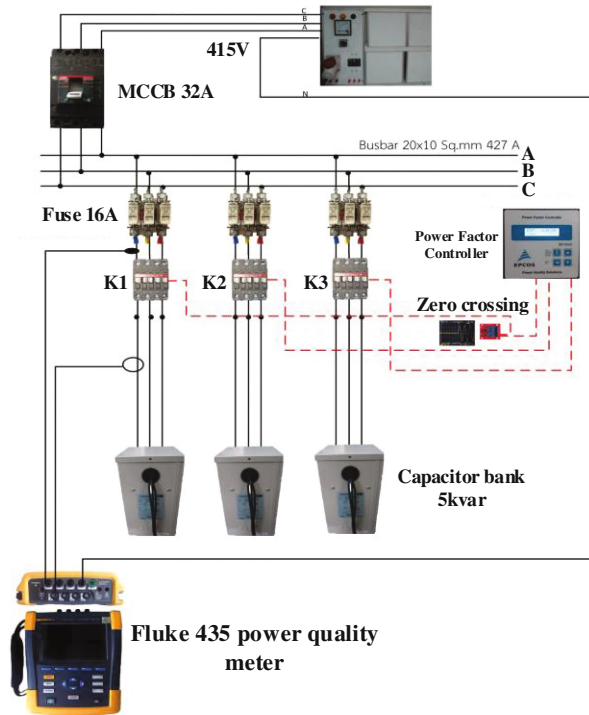
Fig. 2. (continued)

### 3 Experimental Results

The inrush currents from switching capacitors into the experimental setup are measured by using a Fluke 435 power quality meter. There are two case studies: switching capacitors without integrated 7% of reactors and switching capacitors with integrated 7%. In these studies, a zero-crossing detection is installed to control the angle of switching capacitors.

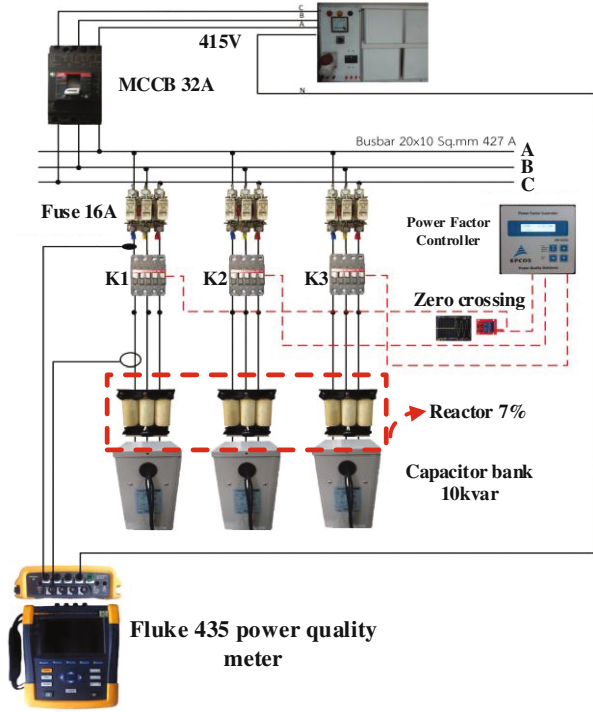
Figure 3(a) gives the schematic diagram of switching capacitors without integrated 7% of reactors. For inrush current measurement, current clamps are installed between magnetic contactors (K1, K2, and K3) and capacitors, while voltage probe installation is set between HRC fuses and the magnetic contactors. For experiment, the test set is supplied from the three-phase voltage of 415 V in the laboratory via a main circuit breaker (32 A, MCCA). The capacitor in each step (1st, 2nd, and 3rd steps respectively) is switched by using the power factor controller to deliver signals to the magnetic contactors K1, K2, and K3. Electrical parameters including the inrush currents are recorded by the power quality meter and results are presented in Table 1. Figure 4 depicts the current and voltage waveforms of switching capacitor bank without integrated 7% of reactors at the phase angles of 0° and 90°.

For the schematic diagram of switching capacitors with integrated 7% of reactors as depicted in Fig. 3 (b), the measurement equipment setting and measurement remain the same case of the switching capacitors without integrated 7% of reactors. In this model, the 7% of reactors are integrated between the magnetic contactors and capacitors in order to reduce effects of the inrush currents; the results are shown in Table 2 and the current and voltage waveforms of the switching capacitors are shown in Fig. 5.



(a) switching capacitors without integrated 7% of reactors

**Fig. 3.** The schematic diagram of switching capacitors (a) switching capacitors without integrated 7% of reactors (b) switching capacitors with integrated 7% of reactors

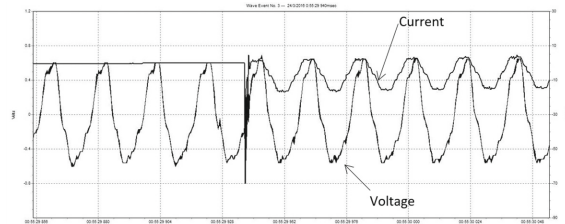
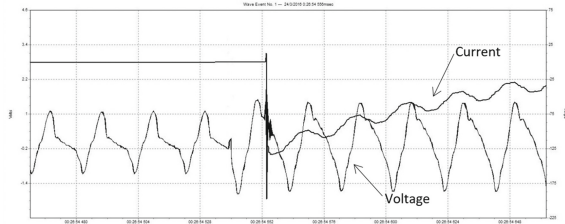
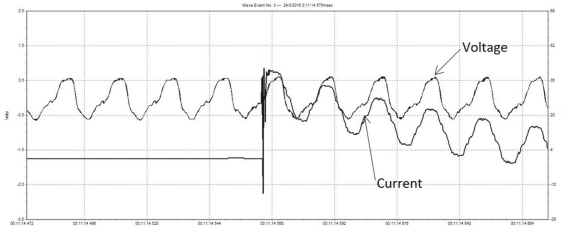
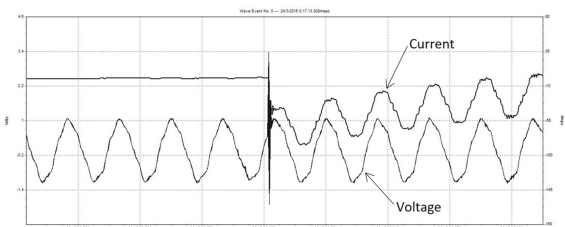


(b) switching capacitors with integrated 7% of reactors

Fig. 3. (continued)

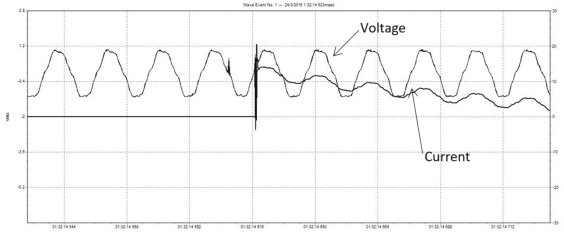
Table 1. Results of inrush current in the case of switching capacitors without integrated 7% of reactors

Phase angle (degree)	1 <sup>st</sup> step			2 <sup>nd</sup> step			3 <sup>rd</sup> step		
	Inrush current (A)	Steady state period (ms)	Current (A)	Inrush current (A)	Steady state period (ms)	Current (A)	Inrush current (A)	Steady state period (ms)	Current (A)
0	-69.98	179	8.12	41.56	161	8.93	-21.37	127	9.23
45	-85.06	336	8.35	52.98	225	8.95	37.60	190	9.09
90	-197.60	712	8.57	-176.52	554	8.97	132.31	595	9.21
135	68.28	350	8.74	52.30	204	9.00	34.59	189	9.05
180	75.21	204	8.21	53.28	194	8.97	22.39	154	9.12
225	-82.92	377	8.32	56.01	194	9.07	33.91	168	9.14
270	197.66	698	8.78	182.76	688	8.88	146.67	611	9.25
315	-82.95	307	8.67	54.38	270	8.98	-36.05	242	9.32

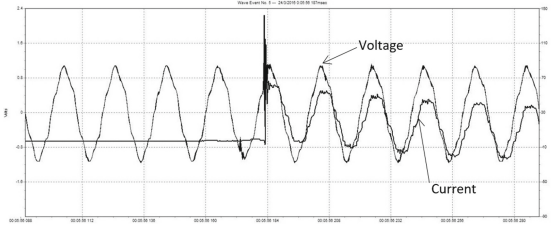
(a) switching capacitors at  $0^\circ$  phase angle in step 1(b) switching capacitors at  $90^\circ$  phase angle in step 1(c) switching capacitors at  $0^\circ$  phase angle in step 2(d) switching capacitors at  $90^\circ$  phase angle in step 2

**Fig. 4.** Current and voltage waveforms of switching capacitor bank without integrated 7% of reactors (a) switching capacitors at  $0^\circ$  phase angle in step 1 (b) switching capacitors at  $90^\circ$  phase angle in step 1 (c) switching capacitors at  $0^\circ$  phase angle in step 2 (d) switching capacitors at  $90^\circ$  phase angle in step 2 (e) switching capacitors at  $0^\circ$  phase angle in step 3 (f) switching capacitors at  $90^\circ$  phase angle in step 3





(e) switching capacitors at 0° phase angle in step 3

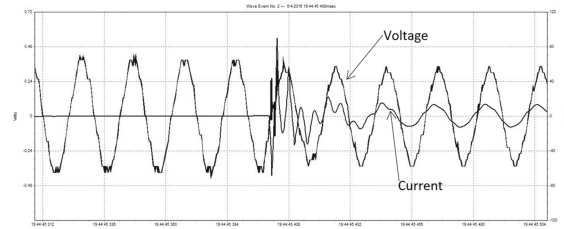
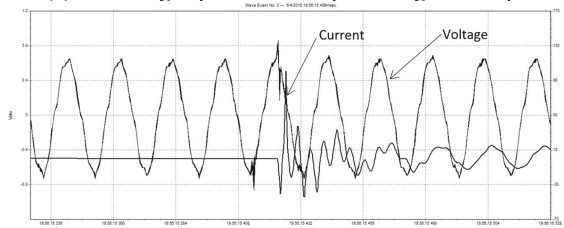
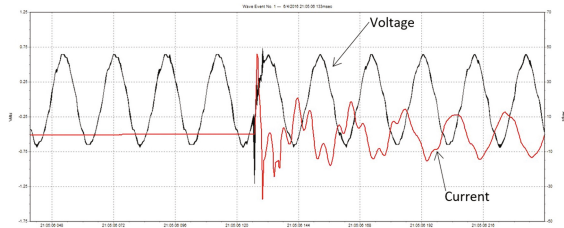
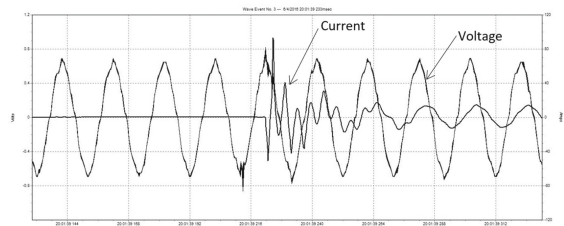


(f) switching capacitors at 90° phase angle in step 3

**Fig. 4.** (continued)

**Table 2.** Results of inrush current in the case of switching capacitors with integrated 7% of reactors

Phase angle (degree)	1 <sup>st</sup> step			2 <sup>nd</sup> step			3 <sup>rd</sup> step		
	Inrush current (A)	Steady state period (ms)	Current (A)	Inrush current (A)	Steady state period (ms)	Current (A)	Inrush current (A)	Steady state period (ms)	Current (A)
0	95.87	79	12.56	91.08	48	14.58	-90.45	39	15.92
45	-95.68	74	12.56	-91.98	53	14.40	-90.92	48	15.90
90	97.98	84	12.45	94.56	68	14.38	92.86	63	15.89
135	-96.45	71	12.57	-91.25	58	14.39	-92.14	52	15.75
180	96.05	64	12.61	-91.09	51	14.39	-91.00	49	15.84
225	97.66	81	12.49	93.87	65	14.40	91.85	55	15.90
270	96.78	73	12.56	-93.56	61	14.14	-91.94	56	15.86
315	95.98	68	12.60	92.87	60	14.19	91.00	51	15.94

(a) switching capacitors at  $0^\circ$  phase angle in Step 1(b) switching capacitors at  $90^\circ$  phase angle in Step 1(c) switching capacitors at  $0^\circ$  phase angle in Step 2(d) switching capacitors at  $90^\circ$  phase angle in Step 2

**Fig. 5.** Current and voltage waveforms of switching capacitor bank with integrated 7% of reactors (a) switching capacitors at  $0^\circ$  phase angle in Step 1 (b) switching capacitors at  $90^\circ$  phase angle in Step 1 (c) switching capacitors at  $0^\circ$  phase angle in Step 2 (d) switching capacitors at  $90^\circ$  phase angle in Step 2 (e) switching capacitors at  $0^\circ$  phase angle in Step 3 (f) switching capacitors at  $90^\circ$  phase angle in Step 3

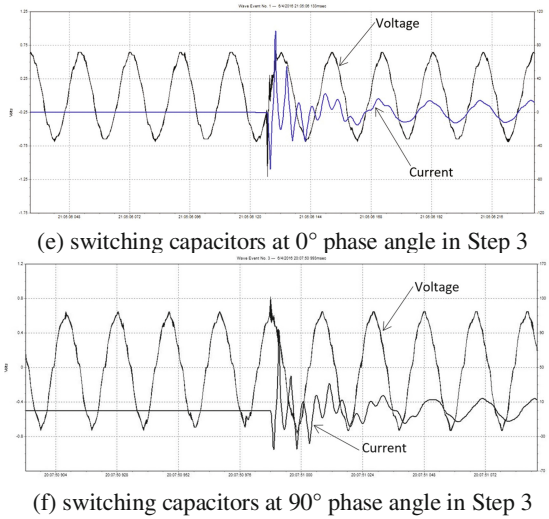


Fig. 5. (continued)

#### 4 Conclusions

This paper aims to study capacitor bank switching transients in a substation by using an experimental test unit. To reduce the effect of switching capacitors, current limiting reactors connected in series with the capacitors are proposed. The results of the switching capacitors without integrated 7% of reactors (see Table 1) show that the inrush current values obtained from the experimental setup have change based on the switched angles of the capacitors. Switching of angles at 90 and 270 degrees causes the maximum inrush current value when comparing with another angles. By contrast, the angles of 0 and 180 degrees give the minimum inrush current value.

For the results of the switching capacitors with integrated 7% of reactors (see Table 2), it can be noticed that inrush current values are almost approximate in each angles of switching capacitors and lower than the inrush currents of the former case. The 7% reactors connected in series with the capacitors increase in an inductance value per a phase, resulting in decreased inrush current values and short periods of time for steady states. However, 7% reactor integration into the experimental setup allows for high current values at the steady states.

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