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An On-Line UPS System that Eliminates the Inrush Current Phenomenon While Feeding Multiple Load Transformers

Syed Sabir Hussain Bukhari[1], Thomas A. Lipo[2] and Byung-il Kwon[1]
[1]Electronic Systems Engineering, Hanyang University, Ansan-si, Gyeonggi-do, 426-791, Korea
[2]Electrical and Computer Engineering, Florida State University, Tallahassee Fl, 32310, USA

***Abstract*—Numerous industrial facilities involve the installation of load transformers with their respective loads. As loads are turned on and off, these transformers are energized and de-energized, respectively, which can cause serious disturbances to sensitive loads. An inrush current, which typically occurs when a transformer is energized, can easily be observed using on-line uninterruptible power supply (UPS) systems feeding such loads. This paper proposes an on-line UPS system that eliminates the inrush current phenomenon caused by the energizing of load transformers. The UPS inverter specifically utilizes a fast acting current control scheme that enables it to regulate current for the load during all energizing conditions of load transformer connected to the UPS system.**

Keywords— Inrush current elimination, on-line UPS systems, mutilple load transformers, current regulator, voltage regulator.

I. Introduction

The quality and consistency of electric power have become major concerns for domestic, commercial and industrial consumers. It is always been vital to provide uninterrupted, reliable and high-quality power to the equipment in life support systems, commercial controls and industrial manufacturing processes, where sudden voltage sags and outages often cause interruptions. In such cases, industrial consumers in particular, often experience major economic losses. Although the public power utility systems are generally quite adequate in most developed countries, studies have revealed that even the best utility system is inadequate to meet the needs of loads in very sensitive applications. Many organizations facing the probability of downtime caused by the utility choose to install UPS systems between the utility and the critical loads in order to guarantee continuous power with constant voltage and frequency to the loads in critical applications under any nonlinear loading condition irrespective of any discrepancy on the utility side. Typical industrial applications that demand a tightly regulated power supply include semiconductor processing, EMC testing, EMI testing and magnetic field generation and mainly rely on the consistent power supply of a UPS system [1]–[3].

On-line UPS systems feeding multiple loads and their respective load transformers have been extensively used in the semiconductor and flat panel display industries due to their compact physical size, higher power quality and greater dependability compared to other UPS topologies [4]. Many industrial facilities install load transformers for the electrical isolation of loads or for voltage matching purposes. Thus, a UPS system frequently has to deliver its power to the loads through these transformers. Although these facilities operate around the clock, some equipment may have to switch on and off periodically depending on the production processes and forecast. The engagement and dis-engagement of such loads also involves the switching on and off of the load transformers. An inrush current phenomenon, which frequently occurs when a transformer is energized, is often experienced when another load is engaged [4]. The magnitude of such transient currents can reach 2–6 times the rated current and persists for many cycles, which can cause a temporary voltage drop and can activate the over-current protection of the UPS system [5]. In addition to the operation failure, an inrush current may affect the load transformer's lifetime by increasing the electrical and mechanical stresses on its windings [6]–[7]. The enormity of these inrush transient currents usually depends on the operating conditions and parameters of the load transformers to be engaged [8].

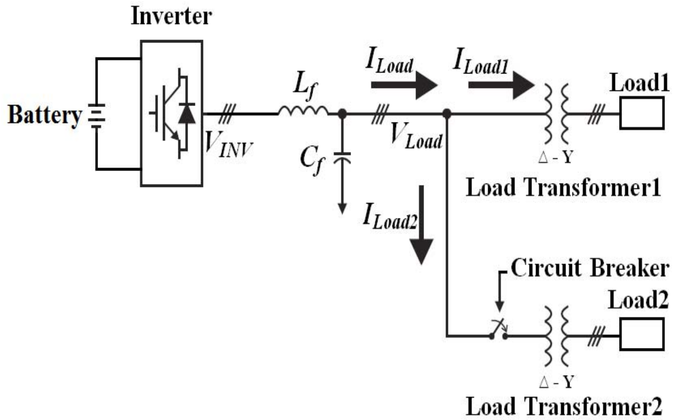


Fig. 1. One-line diagram of an on-line UPS system feeding multiple load transformers.

Numerous techniques have been proposed to reduce these inrush transient currents, such as introduction of resistors or reactors when the transformer is energized [9]. This solution is effective but requires a large power distribution panel to accommodate the resistors, electromechanical switches and breakers, which increases the overall size and cost of the system. Gradually increasing the magnitude of the applied voltage is also effective for reducing the inrush current when the transformers are energized [9]–[12], but it may disturb other transformers and loads that are already on-line. Maintaining the flux linkages of on-line load transformers and the load transformers that are switched-in through closed-loop flux compensation is the most recent technique to reduce inrush currents; however, in this the phenomenon still persists, although with a reduced magnitude. A cost-effective inrush current elimination technique for on-line UPS systems with a simple control strategy for such circumstances remains to be determined [4].

This paper proposes a novel on-line UPS system that eliminates the inrush current phenomenon powering multiple load transformers, by using a swift performing current regulated voltage source inverter (CRVSI) to supply the supplementary current caused by the switching-in of other loads. One of the recently developed high bandwidth control schemes, which were formerly designed at variable frequency motor control is used by the current controller algorithm [13]. On the other hand, these control schemes are also ideally appropriate for controlling AC currents with any balanced load. The load currents of the UPS system are varied sinusoidally in compliance with the supplementary load demand during the engagement of other loads. The high-speed regulating action eliminates the likelihood of any transient inrush currents during the switching-in of other loads. In addition, the proposed on-line UPS system offers considerable reduction in transient currents for the switching-in load transformers.

II. Operating Principle

In previous work, a current regulated voltage source inverter (CRVSI) based upon a high bandwidth PI closed-loop control system has been used to eliminate the inrush current during the switching-in of an auxiliary load while feeding a main load [14]. The applications of the proposed current control scheme are further extended here to propose an on-line UPS system that eliminates the inrush current phenomenon when it is feeding multiple load transformers. A typical on-line UPS system powering two loads through their transformers is shown in Fig. 1. In the given figure, Load1 along with transformer1 are in operation i.e, online, whereas load2 and transformer2 are off-line. At a certain moment, when $t = t_{Load2}$, load2 and load transformer2 are connected to the UPS system through a circuit breaker. A significant transient inrush current is observed for the on-line UPS system when transformer2 is switched-in. The amplitude of such a transient current, which is produced due to the energizing of load transformer2, is expressed as a function of time in equation (1).

$$I(t) = \frac{\sqrt{2}V_m}{Z} * K_w * K_s * \{\sin(\omega t - \varphi) - e^{\frac{-(t-t_0)}{\tau}} . \sin\alpha\} \quad (1)$$

where V_m is the maximum applied voltage, Z is the total impedance under the inrush current, φ is the switching angle of load transformer2, t is the time at which transformer2 is energized ($t=t_{Load2}$), t_0 is the point at which the core saturates, τ is the time constant of the transformer winding under inrush conditions, and α is a function of t_0, K_w and K_s that accounts for the three-phase winding connection and short circuit power.

The peak value of the inrush current for on-line UPS system during switching-in of load transformer2, can be calculated by the equation (2)

$$I_{peak} = \frac{\sqrt{2}V_m}{\sqrt{(\omega.L)^2 + R^2}} \left(\frac{2.B_n + B_r + B_s}{B_n}\right) \quad (2)$$

where L and R are the air core inductance and total DC resistance of the transformer, B_n and B_r are the normal and remanent flux densities of the transformer core, respectively and B_s is the saturation flux density of the core material [15].

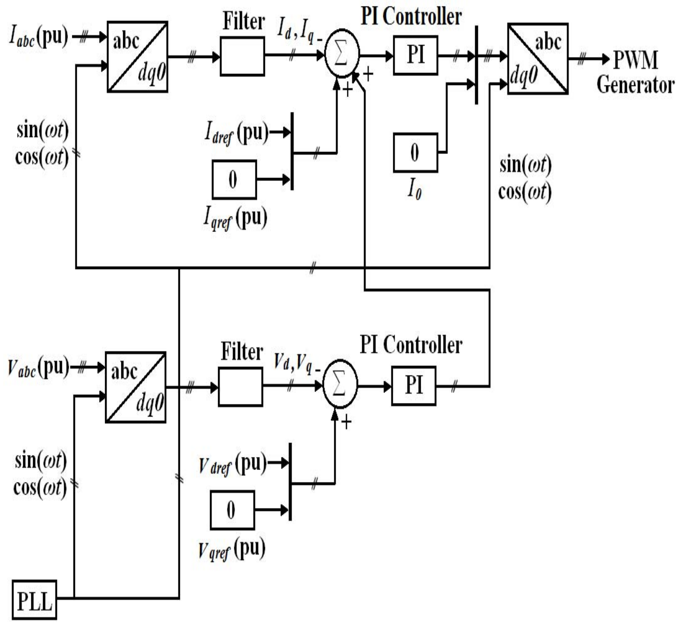


Fig. 2. Current control scheme for the inverter of the proposed on-line UPS system in *dq0* frame of reference.

Above equations suggest that the magnitude of the inrush transient current for the on-line system, when load transformer2 is switched-in is dependent on the parameters of the load transformer2 and its switching conditions.

The inverter of the proposed on-line UPS system shown in Fig. 1 employs a current controller executed in the synchronously rotating reference frame, as shown in Fig. 2. To perform the proposed operation during the switching-in of loads, the inverter of the proposed UPS system utilizes a control strategy that consists of a voltage regulator and a current regulator. The three-phase measured load currents I_{abc} (pu) and voltages V_{abc} (pu) are used as feedback for these regulators. The signals are converted from the *abc* frame of reference to the *dq0* frame of reference using Park's transformation equations. After this conversion, I_d, I_q and I_o currents and V_d, V_q and V_o voltages are filtered to obtain the I_d and I_q currents and V_d and V_q voltages for comparison with the reference current and voltage commands. Error signals are generated after each comparison and are then forwarded to PI controllers of the current and voltage regulators, respectively. The integrator in the voltage regulator always takes on a value such that it is equal to the current I_{load} that exists before the switching-in of load transformer2. When load transformer2 is switched-in, the load voltage (V_{Load}) drops in accordance with the ratings of load transformer2, but it attains the rated 1 p.u value after several half cycles. However, the load currents increase sinusoidally according to the load2 rating. The operation of the proposed on-line UPS system during the switching-in of several loads at different switching conditions is highly dependent upon the values of control gains of both the current and voltage regulators. The per unit values for the proportional gain (K_p) and the integral gain (K_i) of the PI voltage regulator were selected as 0.01 and 100, respectively. The controlled signals of the PI voltage regulator are fed to the summer of the PI current regulator. The proportional (K_p) and the integral gains (K_i) of PI current regulator were selected as 10 and 110, respectively. The output of the PI current controller after combining with I_o is transformed from the *dq0* frame of reference into the *abc* frame of reference according to the inverse Park's transformation. These controlled *abc* signals are then fed to the PWM generator for the required switching of the inverter to the control current, which is then used to avoid any possibility of inrush current during the switching-in of other loads while several loads are already on-line.

Although the generation and magnitude of inrush currents depend upon the magnetic properties and energization conditions of load transformers, the results in this paper are obtained for one specific magnetic property of load transformers. The impedances of the load transformers used for the simulations are given in Table 1.

TABLE 1
IMPEDANCE VALUES OF LOAD TRANSFORMERS

R_1	L_{l1}	R_2	L_{l2}	R_m	L_m
0.0048 (p.u)	0.0024 (p.u)	0.0048 (p.u)	0.0024 (p.u)	500 (p.u)	250.01 (p.u)

III. RESULTS AND DISCUSSION

To validate the proposed on-line UPS system that eliminates the inrush current phenomenon while feeding multiple load transformers, the system shown in Fig. 1 was used for the simulations. The simulations were performed using MATLAB/SIMULINK and the system parameters are as follows:

- Supply/Grid: 220V, 60 Hz;
- UPS system inverter: Output voltage 220V, 60 Hz and switching frequency is 20 kHz. DC bus voltage is 365 V.
- Load Transformer1: 3.0 kVA, 220/220 V (Δ-Y connection);
- Load Transformer2: 500 VA, 220/220 V (Δ-Y connection);
- Load1: 600 VA passive load, operating at 220 V.
- Load2: 400 VA passive load, operating at 220 V.
- Filter: An LC output filter is used at the inverter output. The inductance (L_f) is 20 mH, and the capacitance (C_f) is 10μF.

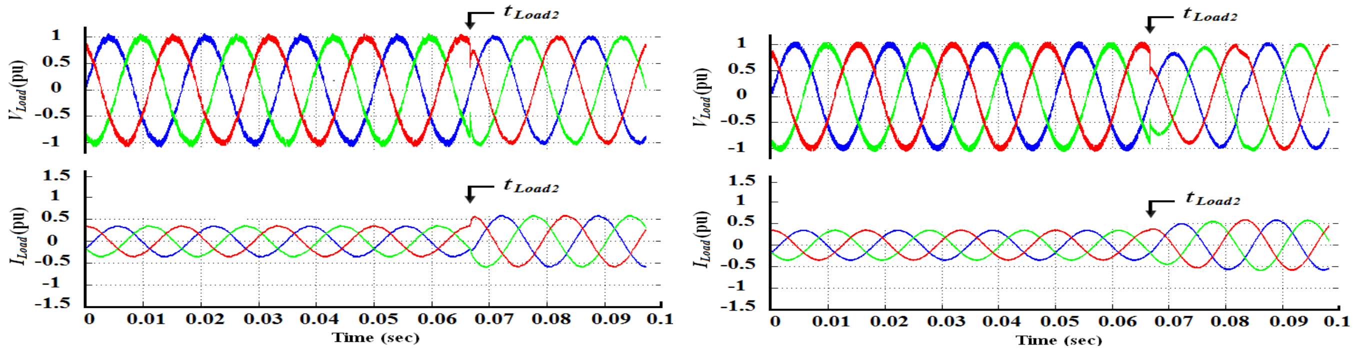
The transient behavior of the conventional on-line UPS system during the switching-in of load transformer2 is shown in Figs. 3–8. A system with the parameters given above is simulated to obtain the load current (I_{Load}) and voltage (V_{Load}). An LC filter similar to that used for the proposed on-line UPS system is used for the conventional on-line UPS system in order to provide a better comparative analysis between the two. In the simulations of the conventional UPS system, load transformer1 and load1 are on-line. When $t= t_{Load2}$, load transformer2 is engaged with the output of the UPS system through a circuit breaker. A significant inrush current phenomenon is observed for the conventional UPS system when load transformer2 is connected. Since the transient inrush current phenomenon for the on-line UPS system feeding multiple load transformers depends on the operating conditions of load transformer2, the system is simulated during different switching-in angles (φ) of load transformer2. Figure 3(a) shows the simulation results for the conventional on-line UPS system when load transformer2 is switched in at an angle of 0 deg. of phase A. The simulation results for the same UPS system shown in Figs. 4(a)–8(a) are obtained when the switching angles of load transformer2 are 60, 120, 210, 240 and 270 deg. of phase A, respectively. The effects of the switching angle of load transformer2 on the magnitude of the load currents (I_{Load}) over the wide range of energizing angles for the conventional on-line UPS system are illustrated in Fig. 9(a). As seen in Fig. 9(a), the highest magnitude of the load current (I_{Load}) for the conventional on-line UPS system with the given parameters is observed when load transformer2 is switched-in at an angle of 240 deg. of phase A. Figures 10(a) and 11(a) show the maximum magnitude of the phase to phase load1 currents (I_{Load1}) and load2 currents (I_{Load2}), respectively.

In most industrial facilities, the distance between the load transformers and the installed UPS system may not be the same, because it varies in accordance with the operational applications of loads in industrial facilities. Equation (2) suggests that a greater distance between load transformer2 and the UPS system corresponds to a lower magnitude of the inrush current and a faster amplitude decay of the inrush current.

A. Behavior of the proposed on-line UPS system

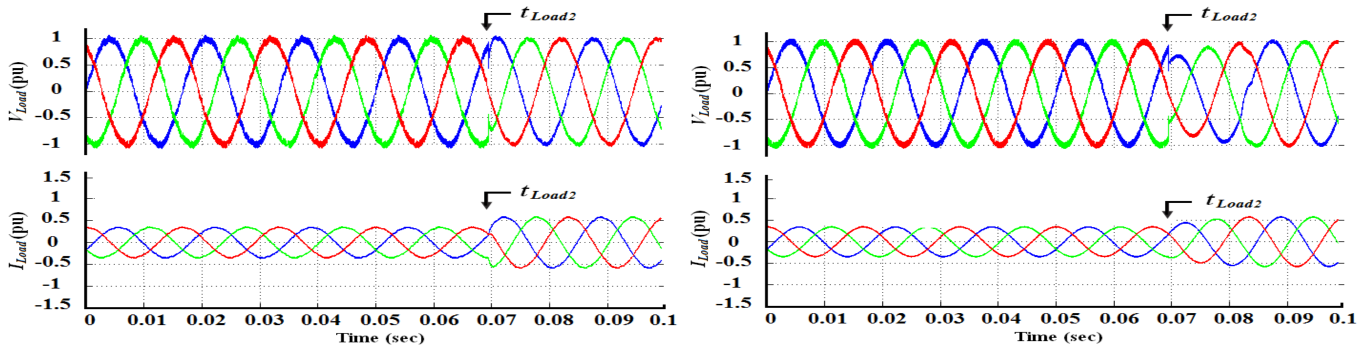
Under the same switching and loading conditions used for the conventional on-line UPS system, the system shown in Fig.1 is simulated in order to investigate the performance and behavior of the proposed on-line UPS system. The performed simulations of load current (I_{Load}) and voltage (V_{Load}) for the proposed on-line UPS system are shown in Figs. 3–8. As seen from the simulation results, the load currents (I_{Load}) and voltages (V_{Load}) for the on-line UPS system after the switching-in of load transformer2 remain constant and never exceed the prescribed value. The performance of the proposed double-conversion on-line UPS system is validated during the different operational conditions for load transformer2, as discussed for the conventional system. The simulation results for the proposed on-line UPS system when load transformer2 is switched-in at an angle of 0 deg. of phase A, are shown in Fig. 3(b). Figures 4(b)–8(b) show the simulation results when the switching-in angles for load transformer2 are 60, 120, 210, 240 and 270 deg. of phase A, respectively.

Figures 9(b)–11(b) show the maximum magnitude of three-phase load currents (I_{Load}), load1 currents (I_{Load1}) and load2 currents (I_{Load}) after the switching-in of load transformer2 during different switching-in conditions. As seen in Fig. 9(b), the maximum magnitude of the phase-to-phase load currents (I_{Load}) is constant and never exceeds the prescribed values after the switching-in of load transformer2. However, the magnitude of generation of the inrush current for load transformer2 is reduced by more than 200%.



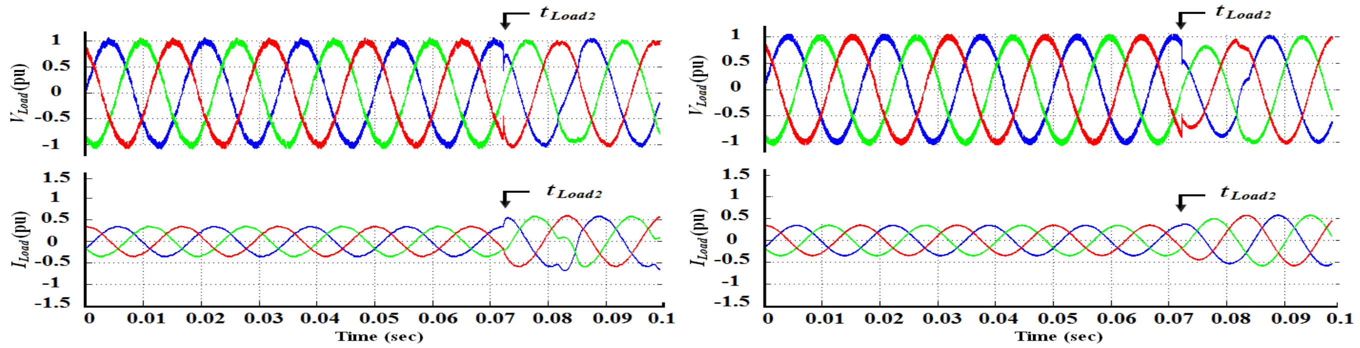
(a) (b)

Fig. 3. Transient performance of the on-line UPS system when load transformer2 is switched in at an angle of 0 deg. of phase A. (a) I_{Load} and V_{Load} for the conventional UPS system, (b) I_{Load} and V_{Load} for the proposed UPS system.



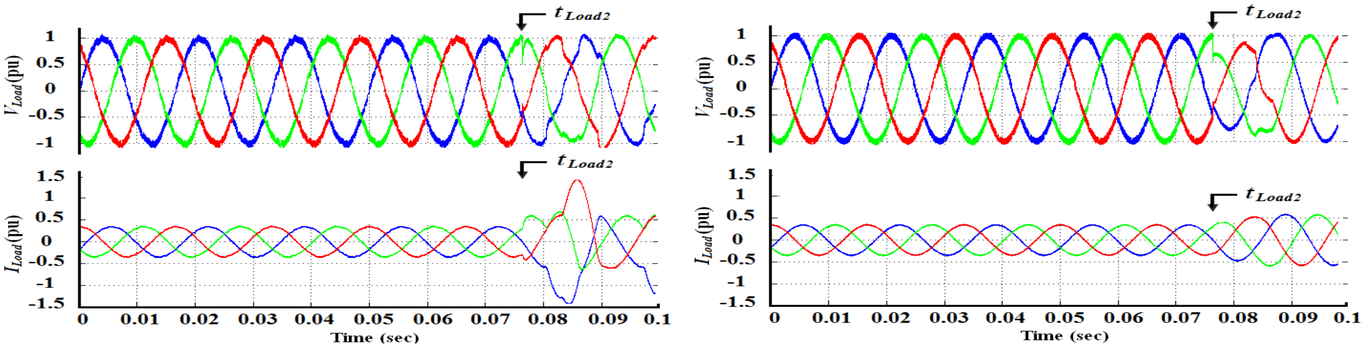
(a) (b)

Fig. 4. Transient performance of the on-line UPS system when load transformer2 is switched in at an angle of 60 deg. of phase A. (a) I_{Load} and V_{Load} for the conventional UPS system, (b) I_{Load} and V_{Load} for the proposed UPS system.



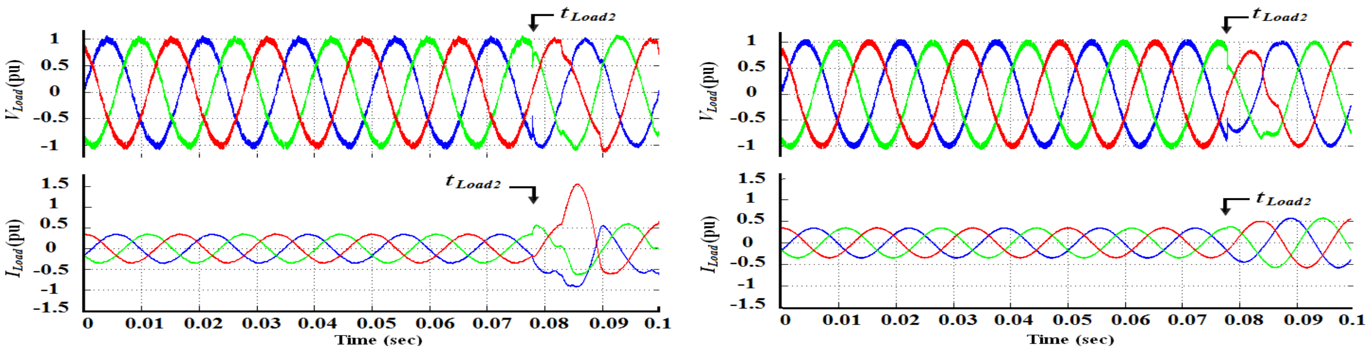
(a) (b)

Fig. 5. Transient performance of the on-line UPS system when load transformer2 is switched in at an angle of 120 deg. of phase A. (a) I_{Load} and V_{Load} for the conventional UPS system, (b) I_{Load} and V_{Load} for the proposed UPS system.



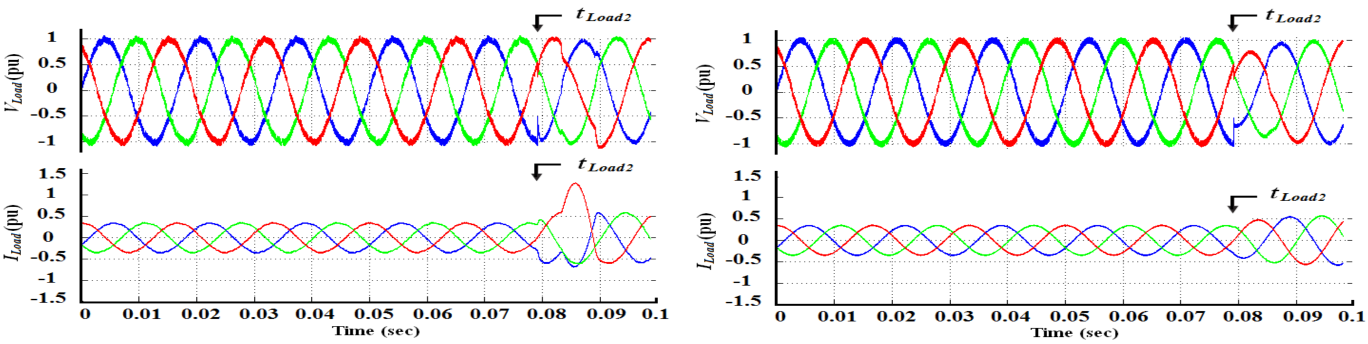
(a) (b)

Fig. 6. Transient performance of the on-line UPS system when load transformer2 is switched in at an angle of 210 deg. of phase A. (a) I_{Load} and V_{Load} for the conventional UPS system, (b) I_{Load} and V_{Load} for the proposed UPS system.



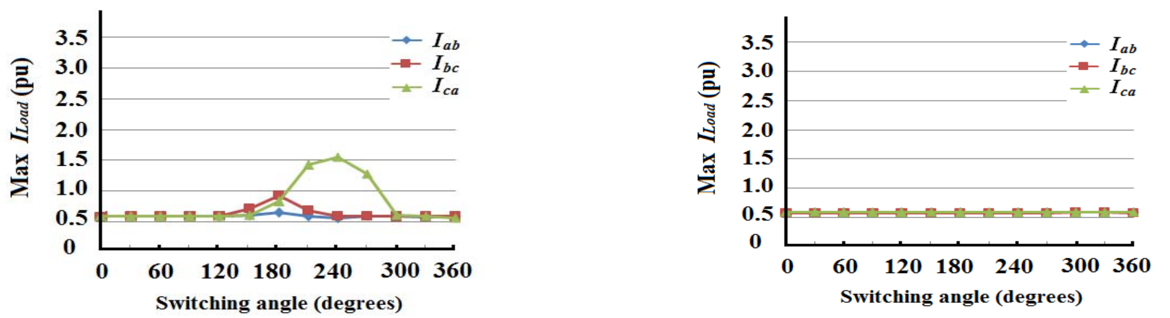
(a) (b)

Fig. 7. Transient performance of the on-line UPS system when load transformer2 is switched in at an angle of 240 deg. of phase A. (a) I_{Load} and V_{Load} for the conventional UPS system, (b) I_{Load} and V_{Load} for the proposed UPS system.



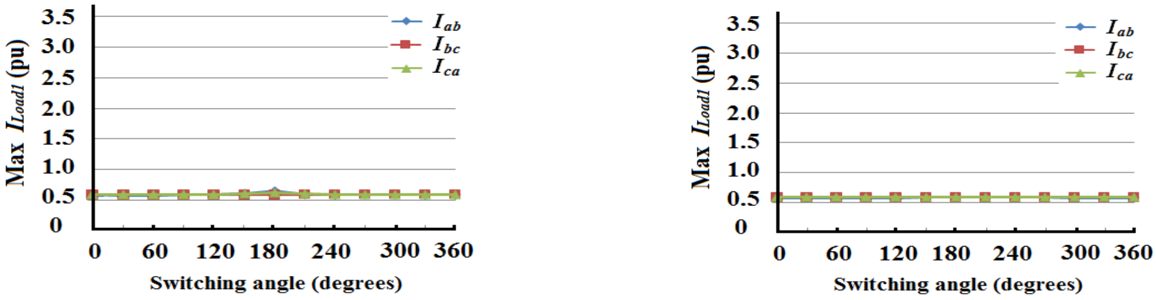
(a) (b)

Fig. 8. Transient performance of the on-line UPS system when load transformer2 is switched in at an angle of 270 deg. of phase A. (a) I_{Load} and V_{Load} for the conventional UPS system, (b) I_{Load} and V_{Load} for the proposed UPS system.



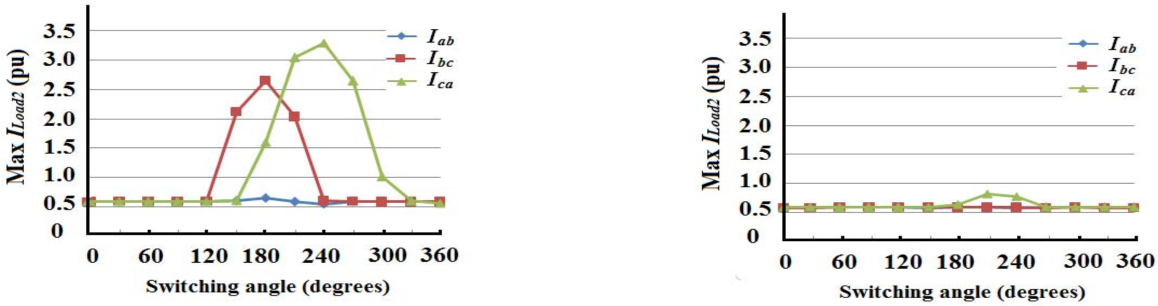
(a) (b)

Fig. 9. Max. magnitude of I_{Load} after switching-in of load transformer2 during different switching-in angles, for the (a) conventional on-line UPS system, and (b) proposed on-line UPS system.



(a) (b)

Fig. 10. Max. magnitude of I_{Load1} after switching-in of load transformer2 during different switching-in angles, for the (a) conventional on-line UPS system, and (b) proposed on-line UPS system.



(a) (b)

Fig. 11. Max. magnitude of I_{Load2} after switching-in of load transformer2 during different switching-in angles, for the (a) conventional on-line UPS system, and (b) proposed on-line UPS system.

IV. Conclusion

An on-line UPS system that eliminates the inrush current phenomenon during the switching-in of multiple load transformers using a standard current regulated voltage source inverter is proposed in this paper. A fast responding control system enables the inverter to regulate the load currents of the UPS systems during different operational conditions for load transformers. Furthermore, the proposed on-line UPS system considerably mitigates the inrush current phenomenon for switched-in loads.

Complete elimination of inrush currents through the use of a simple control strategy with similar volume to the conventional topology, makes the proposed on-line UPS system an economical and cost-effective solution for sensitive load applications.

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