An Inrush Current Elimination Technique for Line-Interactive UPS Systems During Switching-in of an Auxiliary Load While Feeding a Main Load

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Abstract

Most industrial facilities involve use of various types of auxiliary loads in addition to a main sensitive load. Each of these loads are generally accompanied by load transformers. As these auxiliary loads are switched-in, their transformers also become energized. An inrush current often develops when the transformer is switched-in. This paper proposes an inrush current elimination technique for line-interactive UPS systems during the switching-in of auxiliary load transformers by utilizing a fast acting current regulated voltage source inverter. The proposed inrush current elimination technique is validated by simulation results.

1 Introduction

Line-Interactive Uninterruptible Power Supply (UPS) systems have been widely adopted to provide uninterrupted, reliable and high quality power to equipment in critical industrial, commercial and domestic applications under both normal and abnormal utility power conditions [1]. In various industrial applications the line-interactive UPS system may have to feed other auxiliary loads in addition to the main sensitive load. Since these auxiliary loads are connected to the UPS system through transformers for their electrical isolation or voltage matching, thus a UPS system must deliver its power to these loads through their respective transformers. Although the equipment in critical applications operates around the clock, some auxiliary loads may switch on and off during the day depending on the product production and scheduling. Consequently the transformers in front of them are also switched on and off [2]. A significant transient inrush current, which often occurs when the transformer is energized, can readily be observed during the energizing of these auxiliary loads and causes a temporary voltage drop which could trigger the over-current protection of the UPS system. Triggering the over-current protection for the UPS system could result in the termination of a critical application. Moreover, this inrush current can, over time, cause equipment damage.

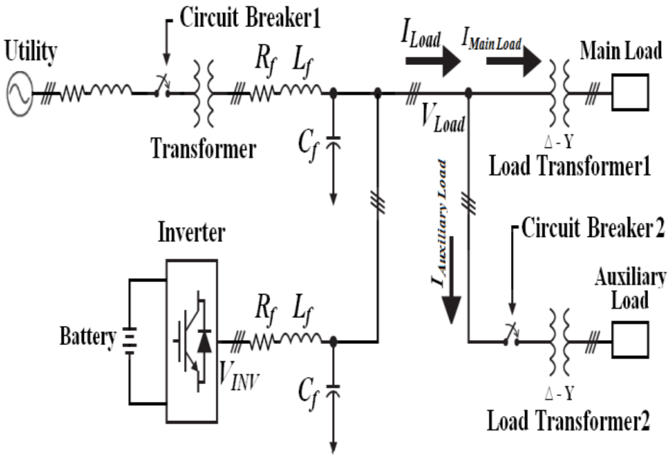

Figure 1: One-line diagram of the proposed line-interactive UPS system with the main and auxiliary loads.

In either case an industrial consumer could bear a substantial financial loss. The magnitude of inrush current caused by the energizing of load transformer usually depends upon the parameters of the transformer itself and its operating conditions.

Numerous proposed techniques have been suggested to mitigate transformer inrush current by different researchers that can be used to reduce the inrush current phenomenon. One method is by inserting resistors when the auxiliary load is switched-in [3]. The solution is effective but to accommodate these resistors and electromechanical switches or breakers, a large power distribution panel is required. Another method is by gradually increasing the magnitude of the applied voltage of the auxiliary load [3]. However, this method may disturb the main load which is already on-line.

Alternatively, a method involving maintenance of the flux linkages of the main and auxiliary load transformers through closed-loop flux compensation [2] could be adopted. However the inrush current phenomenon still persists although with a reduced magnitude. A cost effective inrush current elimination technique with a simple control strategy for such a scenario is still a question to be completely resolved.

This paper proposes a new solution for inrush current elimination for line-interactive UPS system during switching-in of auxiliary loads utilizing a fast acting current regulated voltage source inverter to supply the additional current caused by the switching-in of the auxiliary load. The current controller algorithm utilizes recently developed high bandwidth strategies originally aimed at variable frequency motor control [4]. However, they are also ideally suitable for directly controlling AC currents with any balanced load both with and without an associated EMF (i.e. motor load). The load currents for the UPS system are varied sinusoidally in accordance to the additional load demand during the switching-in of auxiliary load. The fast regulating action eliminates the possibility of any transient inrush current during switching-in of auxiliary loads which occur while feeding the main sensitive load. In addition this solution also results in the reduction of the inrush current phenomenon for auxiliary load transformer.

2 Operating Principle

A current regulated voltage source inverter based upon a high bandwidth PI closed-loop control system was proposed to reduce the inrush current phenomenon for a line-interactive UPS system in [1]. In this paper the current control strategy for such a line-interactive UPS system is further extended to solve the inrush current problem during switching-in of auxiliary loads when it is already powering the main sensitive load. Figure 1 shows a line-interactive UPS system as proposed in [1] feeding two loads i.e. the main load and an auxiliary load through their respective load transformers.

Consider first that the main load together with load transformer1 are in operation i.e. on-line, whereas the auxiliary load along with the load transformer2 are off-line. At a certain moment when $t= t_{Auxiliary\ Load}$, the auxiliary load along with its load transformer2 are connected to the UPS system through a circuit breaker. A significant transient inrush current will typically be observed as load transformer2 is switched-in. In general the amplitude of the inrush transient current, produced due to the energizing of a transformer, can be expressed as a function of time as shown in equation (1).

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

where V_m is the maximum applied voltage, Z is the total impedance under inrush current, φ is the switching angle for the transformer, t is the time at which transformer is energized, t_0 is the point at which core saturates, τ is the time constant of transformer winding under inrush conditions, α is the function of t_0, Kw and Ks accounts for three phase winding connection and short circuit power.

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

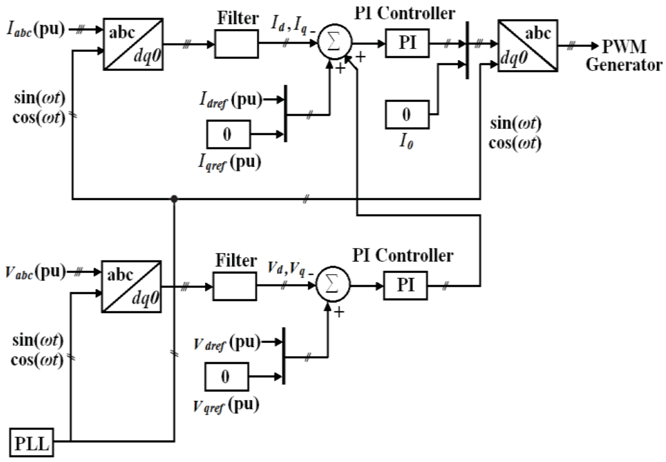

Figure 2: Proposed control scheme for the inverter in *dq0* frame of reference

where V_m is the maximum applied voltage, B_n and B_r are the normal flux density and the remanent flux density of the core of the transformer, B_s is the saturation flux density of the same core material, L is the air core inductance of the transformer, R is the total DC resistance of the transformer. It is clear from the above equations that the value of the inrush current due to energizing any transformer is dependent upon both the parameters of the transformer and the operating conditions at the instant of switching-in.

The inverter of the proposed line-interactive UPS system shown in Figure 1 utilizes a current controller implemented in the synchronously rotating reference frame as shown in Figure 2. To perform the proposed operation and control the current for the UPS system during switching-in, the inverter utilizes a control strategy which consists of a voltage regulator followed by a current regulator. The three phase load currents I_{abc} (pu) and voltages V_{abc} (pu) are measured and used as feedback for these regulators. The signals are converted from the *abc* frame of reference to *dq0* frame of reference by using Park's Transformation equations. After the transformation, the resultant output currents I_d, I_q and I_o and voltages V_d, V_q and V_o are filtered to yield I_d and I_q currents and V_d and V_q voltages for the comparison with the reference currents I_{dref}(pu) and I_{qref} (pu) and voltages V_{dref} (pu) and V_{qref} (pu). The comparison of these currents and voltages results in error signals which are forwarded to the PI controllers of the current regulator and voltage regulator 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. 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 PI voltage regulator are fed to the summer of PI current regulator. The proportional (K_p) and the integral gains (K_i) of this PI current regulator were selected as 10 and 110. The output of the PI current controller after combining with I_o is transformed back from the *dq0* frame of reference into the *abc* frame of reference through an inverse Park's Transformation. The controlled *abc* current signals are then fed to the PWM generator for the required commutation of the inverter to control current which then avoids any possibility of the inrush current for the line-interactive UPS system during the switching-in of auxiliary load while feeding the main load. Since the main utility supply is fully capable of supplying the load in the steady state, the current command of the inverter can now slowly be reduced to zero resulting in the inverter to be simply "floating" or can be removed completely during steady state operation.

3 Results and Discussion

To validate the proposed inrush current elimination technique the system shown in Figure 1 has been used for the simulation study. The simulations have been performed through MATLAB/SIMULINK and the system parameters are given 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);
Main Load: 700 VA passive load, operating at 220 V.
Auxiliary Load: 300 VA passive load, operating at 220 V.
Filter: Two RLC output filters with the same parameters are used at the inverter and the transformer output as proposed for the line-interactive UPS system in [1]. The filter resistance (R_f) is 1 ohm, inductance (L_f) is 20 mH and the capacitance (C_f) is 10μF for each.

The transient behaviour of the line-interactive UPS system during switching-in of an auxiliary load without the proposed control scheme is shown in Figures 3-6. A system with the above given parameters was simulated to obtain the load current (I_{Load}) and voltage (V_{Load}) for the UPS system as proposed in [1]. In the performed simulations the main load was first connected to the output of the UPS system in addition to the main supply. The inverter is merely floating and supplying none of the load current. At a particular moment when $t = t_{Auxiliary\ Load}$, load transformer2 is connected to the output of the system through a circuit breaker or contactor. A significant inrush current phenomenon can be observed for the UPS system. Since the inrush current depends upon the operating conditions of load transformer2, the system has been simulated during for different switching angles of the load transformer2. Figure 3 shows simulation results when load transformer2 is switched-in at the angle corresponding to 0 deg. of phase A. i.e. at the positive sloped zero crossing of the current.

Simulation results for the same UPS system when the switching angles of the load transformer2 are 60 and 270 deg. of phase A current zero crossing respectively are shown in Figures 4 and 5. The effect of the switching angle of the load transformer2 on the magnitude of the load current (I_{Load}), main load current ($I_{Main\ Load}$) and the auxiliary load current ($I_{Auxiliary\ Load}$) without the proposed control scheme, over a complete cycle of phase A can be observed from the Figures 7-9. As seen from these figures, the highest magnitude of the auxiliary load currents ($I_{Auxiliary\ Load}$) is obtained when load transformer2 is switched-in at the angle of 210 deg. of phase A. This results the highest load current (I_{Load}) magnitude for the line-interactive UPS systems. Simulation results for the load currents (I_{Load}) and voltages (V_{Load}) when the load transformer2 is switched-in at the angle of 210 degrees of phase A are shown in Figure 6.

Simulations of the system of Figure 1 obtaining the load current (I_{Load}) and voltage (V_{Load}) with the proposed control strategy are shown in Figures 10-13. As seen from the simulation results the load currents (I_{Load}) for line-interactive UPS system during switching-in of auxiliary load increases sinusoidally consistent with auxiliary load's ratings. The load voltages (V_{Load}) drops for several of half cycles (not more than 5 half cycles in the given simulations) as the auxiliary load is engaged but then attains its rated 1 p.u magnitude. The performance of the proposed inrush current elimination technique was also validated during different operational conditions of load transformer2.

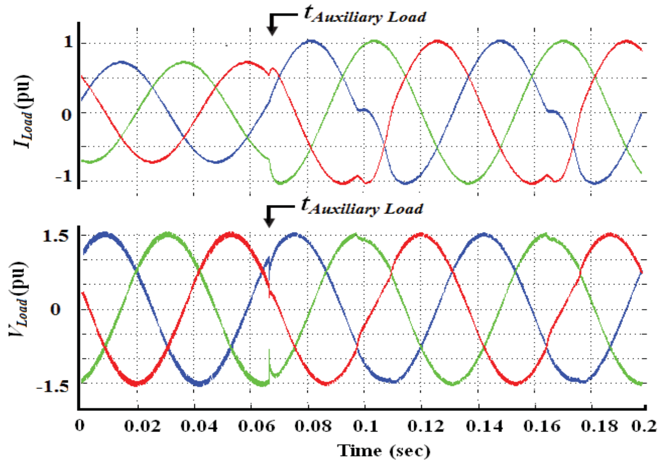

Figure 3: Transient behaviour of line-interactive UPS system during switching-in of an auxiliary load at 0° of phase A, while feeding a main load without the proposed control scheme.

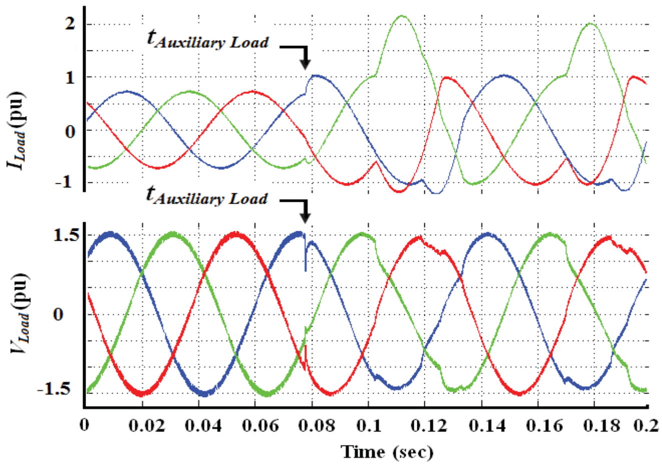

Figure 4: Transient behaviour of line-interactive UPS system during switching-in of an auxiliary load at 60° of phase A, while feeding a main load without the proposed control scheme.

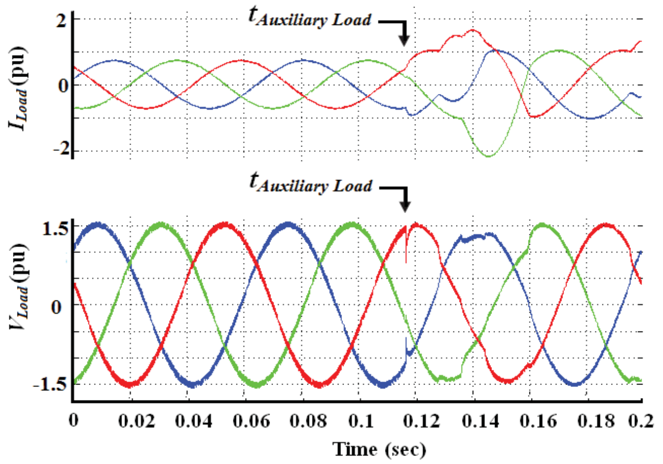

Figure 5: Transient behaviour of line-interactive UPS system during switching-in of an auxiliary load at 270° of phase A, while feeding a main load without the proposed control scheme.

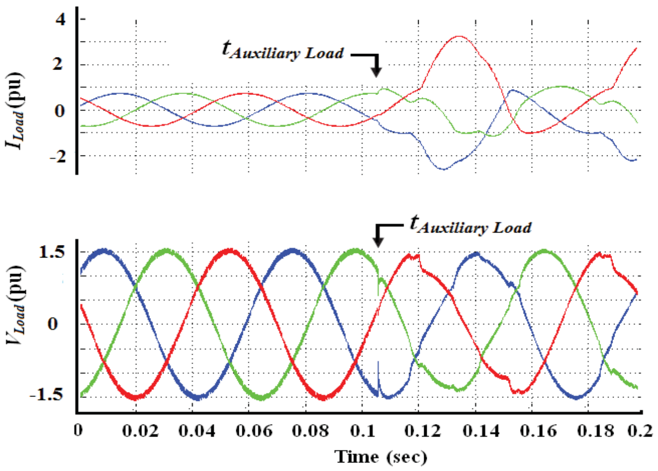

Figure 6: Transient behaviour of line-interactive UPS system during switching-in of an auxiliary load at 210° of phase A, while feeding a main load without the proposed control scheme.

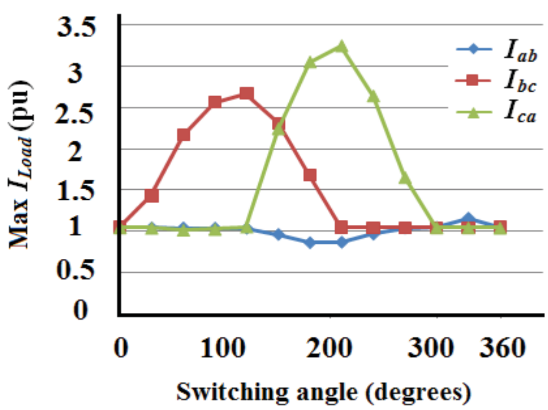

Figure 7: Effect on the magnitude of I_{Load} for the line-interactive UPS system during switching-in of an auxiliary load while feeding a main load without the proposed control scheme.

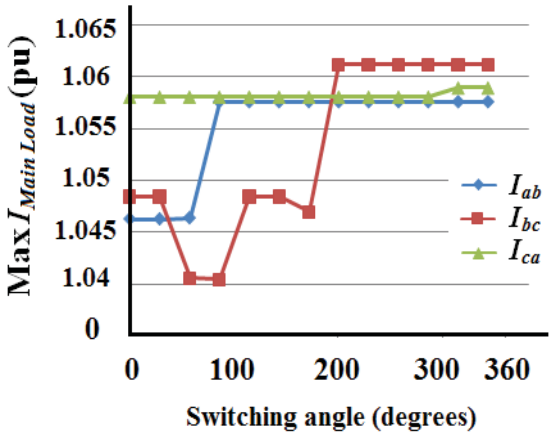

Figure 8: Effect on the magnitude of $I_{Main\ Load}$ for the line-interactive UPS system during switching-in of an auxiliary load while feeding a main load without the proposed control scheme.

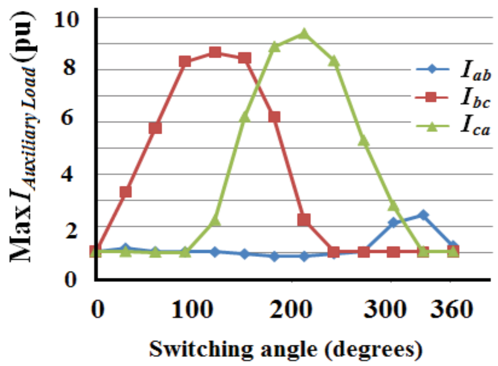

Figure 9: Effect on the magnitude of $I_{Auxiliary\ Load}$ for the line-interactive UPS system during switching-in of an auxiliary load while feeding a main load without the proposed control scheme.

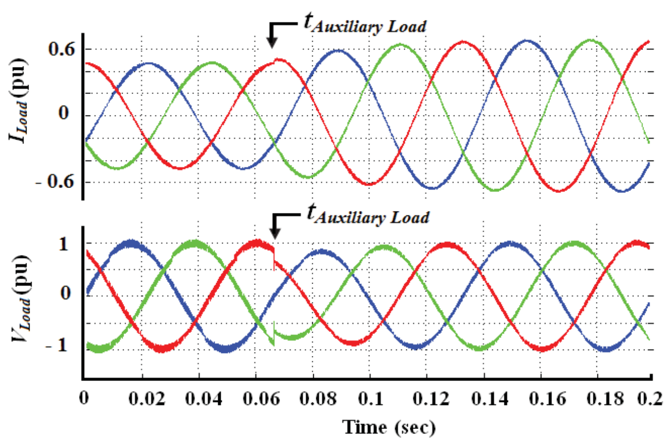

Figure 10: Transient behaviour of line-interactive UPS system during switching-in of an auxiliary load at 0° of phase A, while feeding a main load with the proposed control scheme.

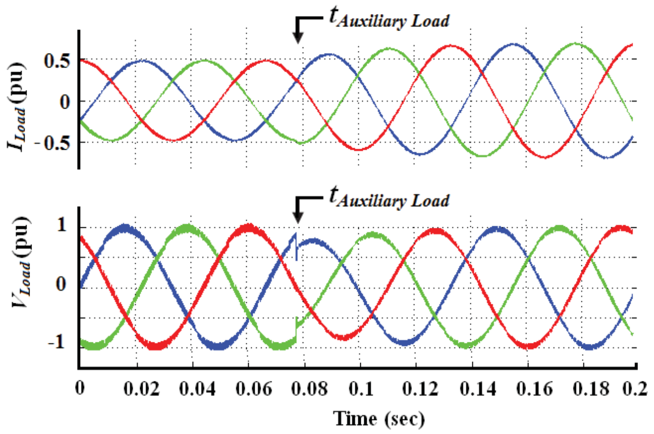

Figure 11: Transient behaviour of line-interactive UPS system during switching-in of an auxiliary load at 60° of phase A, while feeding a main load with the proposed control scheme.

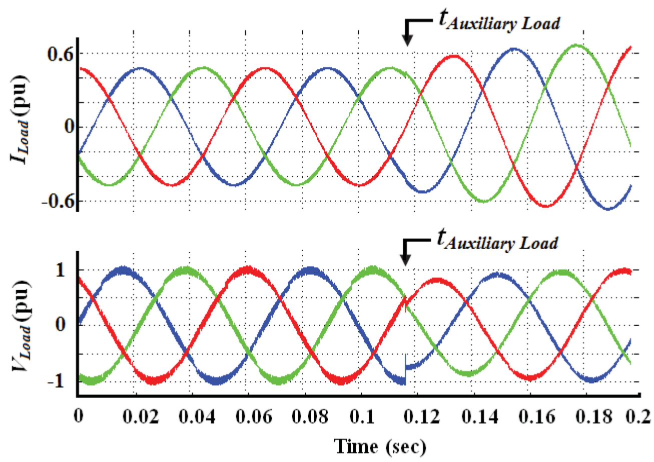

Figure 12: Transient behaviour of line-interactive UPS system during switching-in of an auxiliary load at 270° of phase A, while feeding a main load with the proposed control scheme.

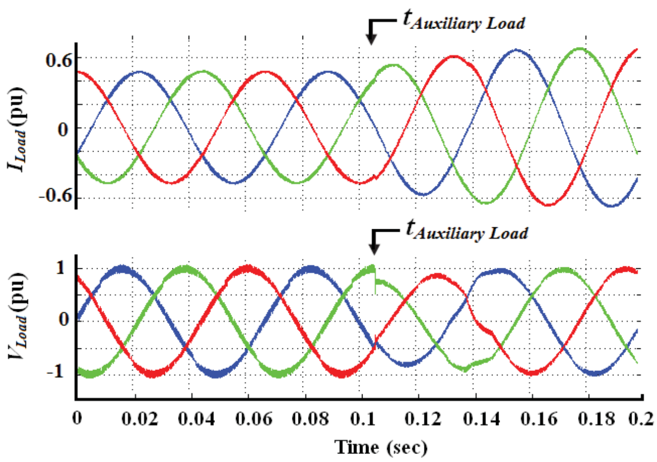

Figure 13: Transient behaviour of line-interactive UPS system during switching-in of an auxiliary load at 210° of phase A, while feeding a main load with the proposed control scheme.

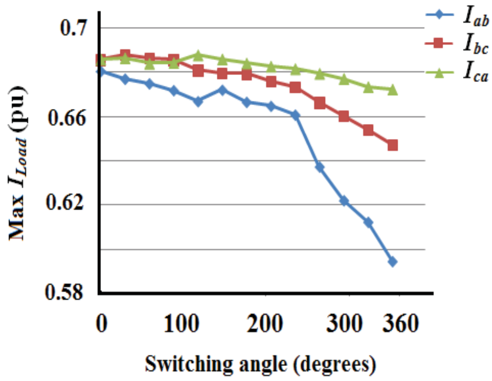

Figure 14: Effect on the magnitude of I_{Load} for the line-interactive UPS system during switching-in of auxiliary load while feeding a main load with the proposed control scheme.

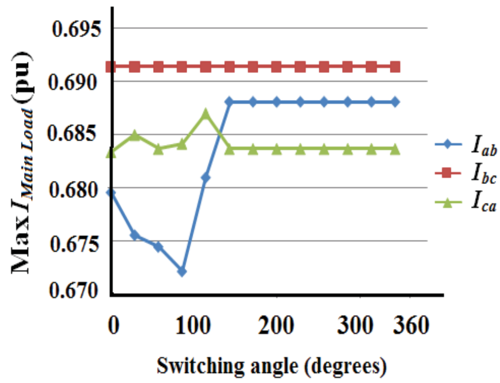

Figure 15: Effect on the magnitude of $I_{Main\ Load}$ for the line-interactive UPS system during switching-in of auxiliary load while feeding a main load with the proposed control scheme.

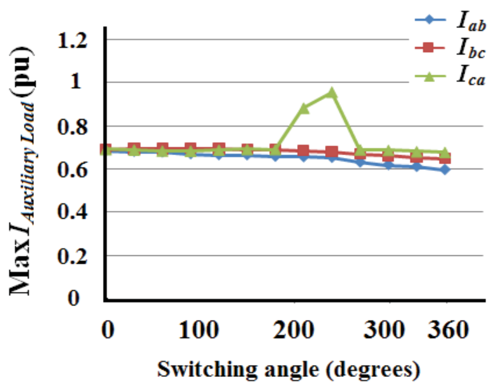

Figure 16: Effect on the magnitude of $I_{Auxiliary\ Load}$ for the line-interactive UPS system during switching-in of auxiliary load while feeding a main load with the proposed control scheme.

The simulation results for the proposed inrush current elimination at the angle of 0 deg. of phase A are shown in Figure 10. In this case the feedback is again engaged but the inverter is not supplying any power before the switch-in transient occurs. Figures 11 and 12 show the results when switching angle of load transformer 2 is 60° and 270° of phase A respectively. To investigate the performance of the proposed inrush current elimination technique the same system was simulated when the load transformer2 is switched-in at the angle of 210 deg. of phase A, the worst case obtained without the control. Simulation results for the load currents (I_{Load}) and voltages (V_{Load}) are shown in Figure 13. Figures 14-16 show that the variation in the magnitude of load current (I_{Load}), main load current ($I_{Main\ Load}$) and the auxiliary load current ($I_{Auxiliary\ Load}$) at the different switching angles of load transformer2 over a complete cycle of phase A. It is apparent that the transient is greatly reduced by using proposed control scheme. From the given results one can observe that the proposed technique not only eliminates the inrush current problem for the line-interactive UPS system but it also beneficially affects inrush current phenomenon for the auxiliary load.

4 Conclusion

An inrush current problem associated with the line-interactive UPS system during switching-in of an auxiliary load while feeding a main load, which was never focused before has been discussed in this paper. This paper proposes that by using a standard current regulated voltage source inverter with a typical current control scheme, an inrush current phenomenon caused by the switching-in of load transformer for a line-interactive UPS system, when another load is already on-line, can be eliminated. A fast responding control system enables the inverter to regulate the load currents of the UPS system during the different operational conditions for auxiliary load transformers. The proposed technique can also be effective for reducing inrush currents for the auxiliary load transformers.

The proposed inrush current elimination technique for the line-interactive UPS system during switching-in of an auxiliary load while feeding the main sensitive load could be proved as economical with simple control strategy during any of the operational conditions of auxiliary load transformers.

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