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A Three-Phase Line-Interactive UPS System to Eliminate the Inrush Current Phenomenon during Switching-in of an Auxiliary Load while Powering the Main Load

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Abstract – Normally, various auxiliary loads are installed along with the main load in industrial applications. Usually, load transformers are used to convey such types of auxiliary loads. The transformers become energized when the loads are turned-on, consequently, high amplitude of inrush current appears at the output of the uninterrupted power supply (UPS) system. To mitigate these high current amplitudes, this manuscript suggests a three-phase line-interactive UPS system to counter the inrush current during the turning-on of the auxiliary load transformer while powering the main load by using a current controlled inverter. Experimental results of a laboratory-sized prototype are provided in the support of the proposed UPS system for validation.

Keywords: UPS systems, Three-phase line-interactive, Inrush currents, Current-controlled inverter.

1. Introduction

During recent years, in critical load application, three-phase line-interactive UPS systems have been widely used to be for uninterruptable, and consistent power to the industrial equipment [1-3]. In several type of applications, auxiliary loads are powered by a line-interactive UPS system besides the main load. Normally for isolation purpose these auxiliary loads are coupled with UPS output by the load transformers; therefore, a UPS system has to power the auxiliary load through its corresponding load transformer. Although the equipment in critical applications works continuously, some of these auxiliary loads might be turned on and off during the working hours, depending on the industry less productive hours and vice versa. Due to this toggling, the transformers installed are energized and de-energized simultaneously [4]. Significant inrush current appears at the output of the line-interactive UPS system due to the energization of the load transformer. The generation of substantial inrush transient current for the system causes a voltage drop at the output of the UPS system and consequently activates the over-current protection device [5]. Triggering the protection device of the line-interactive UPS system concludes in overall suspension of the critical applications. On the other side, a transient inrush current can, with the time span, cause equipment malfunction. Generally in these situations, an industrial consumer might go through a considerable economic damage. The amplitude of the transient inrush current due to the energizing of the load transformer is generally calculated by the transformer's parameters and its operation condition [6].

Many solutions have been presented in literature to eliminate the transformer inrush current phenomenon. Nevertheless, these solutions of inrush current elimination may have some disruptive effects on the UPS system. Authors of [7] have suggested to introduce power resistors and reactors at the output of the line-interactive UPS system as the auxiliary load is turned on. In spite of the fact that the recommendation helps in suppressing the inrush transient current, but incorporation of these reactors, resistors, control circuits, breaker and switches increases the overall size and cost of the UPS system. Similarly, the inrush transient current effect can also be nullified by controlling the applied voltage of the auxiliary load in such a way that it increases slowly [8]. However, this method may affect the main load that is already on-line disruptively. Another method that can be employed for the mitigation of transformer inrush current is to design the load transformer in such a way that the flux of the transformer remain less than the twice the level of the saturation of the core of the transformer under steady-state condition. Thus when the auxiliary load is turned-on, the core of the transformer will not get saturated and the possibility of the inrush current gets eliminated. However, this solution results in the overall increase in the size and the cost of the UPS system. Keeping the fact in the mind that the magnitude of inrush current depends upon the switching angler of the transformer. Hence, controlling the turn-on angle of the auxiliary load at an appropriate phase instant can also be helpful in reducing the inrush current phenomenon for a line-interactive UPS system. This technique not only

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reduces the inrush current magnitude but also decreases the crest factor to the steady state value of less than 1.5. However, it will again effect the main sensitive load that is already on-line. Alternatively, by controlling the flux linkages of the main and auxiliary load transformers implemented in a synchronous frame by flux compensation method could be applied [9]. However, reduced magnitude of the inrush transient current phenomenon still continues in this situation as well.

In this paper, a three-phase line-interactive UPS system is proposed which eliminates the problem of inrush transient current generated by the switching-in of an auxiliary load while powering the main load. In the proposed UPS system, inverter utilizes a fast acting current regulating algorithm, which conveys the additional magnitude of load current caused by the switching-on of the auxiliary load without allowing them to exceed the given value at any instant. The load currents for the proposed system increases sinusoidally with the ratings of the additional load as the auxiliary load is connected. This control scheme is implemented in stationary frame of reference which is simple and easy to implement as compared to other control schemes implemented in synchronous frame of reference or the control schemes based on P+Resonant (P+R) current regulators. Moreover, the proposed three-phase line-interactive UPS system has a single inverter, whereas, the conventional three-phase UPS system have two converters. In light of this comparison it is evident that the proposed system has several advantages including the simplicity, less cost and small size as compared to the conventional UPS systems. Experimental results of a laboratory-sized prototype are provided to be consistent with the theoretical analysis, which validates the correctness of the theory.

2. Principle of Operation

The working principle and performance of both systems i.e. conventional and proposed line-interactive UPS systems are discussed below:

2.1 Conventional three-phase line-interactive UPS system

Fig. 1(a) shows a conventional three-phase line-interactive UPS system having auxiliary and main loads. The conventional system contains two converters, the first converter is in series with the utility and second one is in parallel to the load. In normal condition the load is

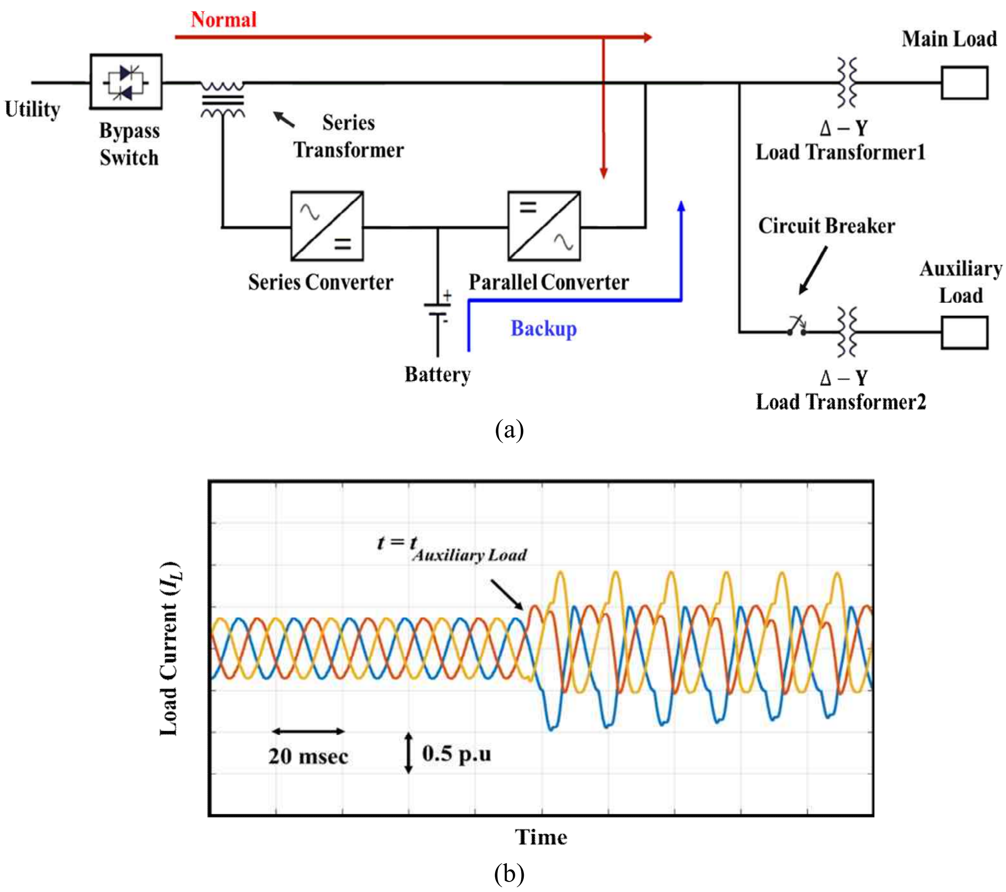


Fig. 1. (a) Simplified diagram and (b) load currents (I_L) for a conventional line-interactive UPS system during switching-in of an auxiliary load while powering the main load

supplied by the utility, meanwhile, the battery is charged through the parallel converter. When the utility fails, the load is disconnected from the utility by opening the bypass switch, the battery starts feeding the load through the parallel converter. On the other side, the series converter controls the output voltage of the UPS system during the fault like voltage sag and swell through the series transformer. Collectively, a three-phase line-interactive UPS system operates in three modes, namely, normal, compensation, and inverter operation mode. Therefore, a line-interactive UPS topology is an essential candidate for installation in industries. On other side drawbacks associated with this line-interactive UPS system includes high cost, large scale, a complex algorithm, and absence of real-time isolation of the load from utility [11].

Generally, a three-phase line-interactive UPS system may have to supply power to supplementary auxiliary loads while powering the main load. Normally, load transformers, which are installed before the loads for isolation purpose, are used to connect the output of the line-interactive UPS system to auxiliary loads. So, a UPS system has to supply the power to the load via load transformers. Although, some paraphernalia in critical application works throughout the day with auxiliary loads may turn on and off around the clock, accordingly to industrial equipment usage with productively demands. In such situation the transformers installed before the load are energized and de-energized round the clock. A significant inrush transient current that normally occurs once a transformer gets energized, can also be witnessed when an auxiliary load is turning-on for a line-interactive UPS system.

The size of the inrush transient current for a line-interactive UPS system during turning-on of an auxiliary load, while supplying main load is dependent on the specifications of the load transformer and its switching instants [12]. Although, in a three phase line-interactive UPS system, inrush transient current is generated in both inverter and compensation modes, but it has more disruptive effects in inverter mode compared to compensation mode.

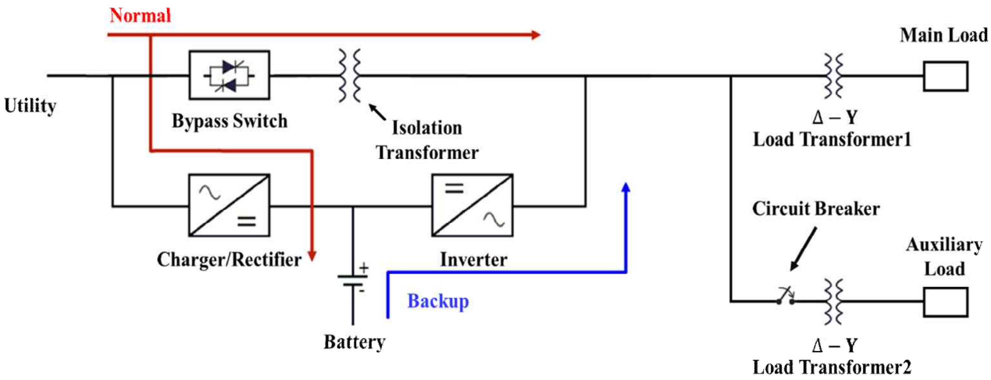
The conventional three-phase line-interactive UPS system's behavior is examined in such a condition as shown in Fig. 1(a), where, main load is online through transformer 1, and, the auxiliary load with transformer 2 is off-line. Load transformer 2 is connected to the inverter of the line-interactive UPS system at instant $t=t_{Auxiliary\ Load}$ with the help of circuit breaker. When the auxiliary load is coupled, a severe magnitude of inrush transient current is observed at the output of line-interactive UPS system and the load current (I_L) reaches a peak of 0.91 (p.u) that is around 75% higher than the rated 0.52 (p.u) load current. Fig. 1(b) demonstrates the behavior of the current for a conventional line-interactive UPS system during the switching-in of an auxiliary load while powering the main load. This investigation of the UPS system is carried out under inverter operating mode with listed system parameters:

Utility/grid: 220 V, 60 Hz
UPS system inverter: 220 V, 60 Hz, switching frequency 20 kHz, DC bus voltage 365 V
Main Load: 1.0 kVA,
Load Transformer1: 3.0kVA, 220/220V (Δ-Y connection)
Auxiliary Load: 400 VA,
Load Transformer1: 500VA, 220/220V (Δ-Y connection)
Inverter output filter: LC filter inductance (L_f) 20 mH, filter capacitance (C_f) 0.1 μF

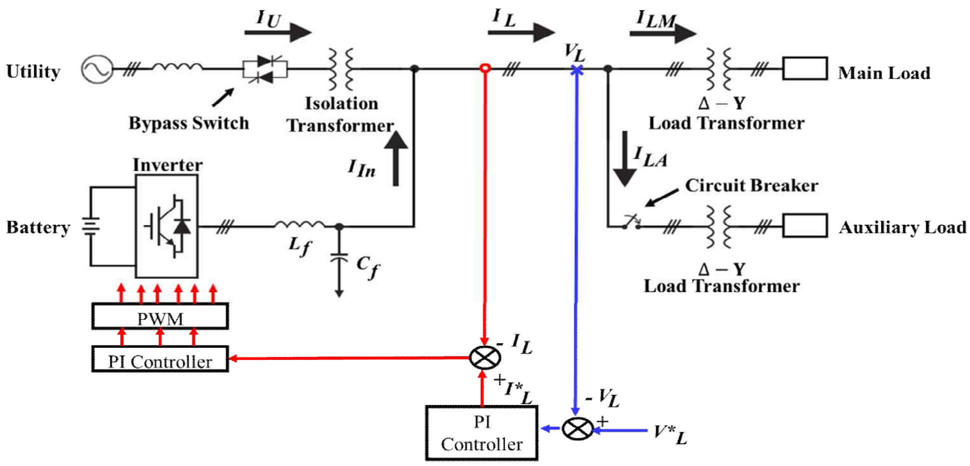
2.2 Proposed three-phase line-interactive ups system

Fig. 2(a) shows a simplified diagram of proposed three-phase line-interactive UPS system, the scenario shown here is of switching of an auxiliary load, meanwhile, supplying power to the main load; mainly, the proposed UPS system contains, a bypass switch, a transformer for isolation between utility and the load, and an inverter which is connected in parallel to the utility and the load. During normal operation, the load is fed from the utility; while the battery is being charged via the connected inverter. Once the aberrant situation occurs and the utility fails, the bypass switch disconnects to isolate the load from utility and the battery start supplying the power to the load via parallel connected inverter. In event of sag, the bypass switch is not opened, the compensation is adjusted by the inverter for the load power. The proposed UPS system contains power conditioning and regulating capabilities. There is only one inverter in the proposed UPS system, it has the advantages of small size, low cast, simple design and high efficiency.

The current control scheme in stationary frame is employed for inverter of the proposed UPS system, as discussed in [13-14]. The stationary frame current control method is adopted instead of well-known *dq0* frame because of the reason that the stationary frame current control scheme is simple and easy to implement. A detailed diagram of the proposed UPS system is shown in Fig. 2(b), where, there are two control loops. The outer loop is basically providing a reference signal (I^*_L) by controlling the output voltage (V_L) of UPS system for inner control loop through PI controller. The inner loop is responsible to adjust the load current (I_L) through PI controller to avoid the generation of any inrush transient current and retain the load current under destructive values once the auxiliary load is switched-on. It is the matter of the fact that the phenomenon of inrush current generates the voltage imbalance as it includes even harmonics. This imbalance condition is observed during the switching-on of the auxiliary load. Since the proposed UPS system is capable of regulating the load voltage during any abnormal grid condition by using the outer control loop employed for the inverter of the proposed UPS system. Hence, it also eliminates the voltage imbalance condition occurred due to



(a)



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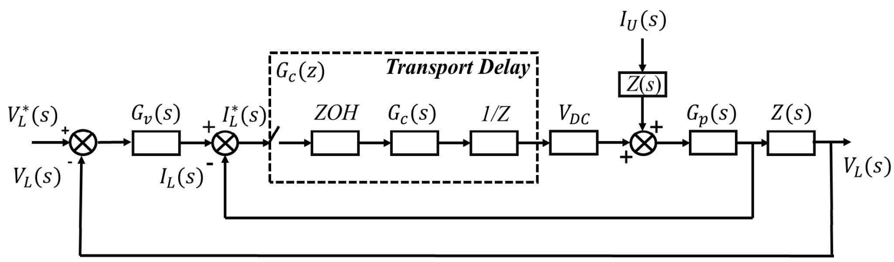
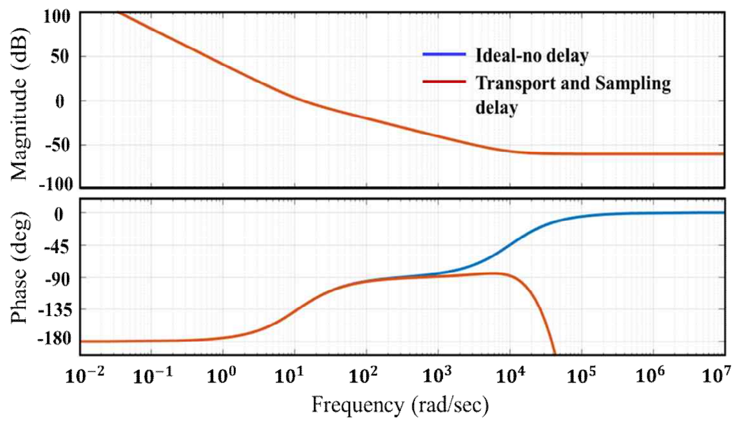


(c)



(d)

Fig. 2. (a) Simplified diagram, (b) complete diagram, (c) average-value model, and (d) bode plot for the implemented controller of the proposed line-interactive UPS system

the generated inrush transient current. Fig. 2(c) presents an average value diagram of the proposed UPS system. In the diagram, $V^*_L(s)$ is the rated load voltage, $V_L(s)$ is the output voltage of the inverter, Z(s) is the load impedance, $G_v(s)$ is the transfer function of the voltage PI controller, $I^*_L(s)$ is the reference load current produced by the PI voltage controller, V_{DC} is the forward gain of the linear amplifier that is used for the PWM modulator, $I_L(s)$ is the controlled output current, and $G_c(s)$ is the transfer function of the PI current controller. This gives an overall transfer function of the system as:

$$V_L(s) = \left[\frac{I^*_L(s)G_c(s)V_{DC}G_p(s) + I_U(s)G_p(s)}{1+G_c(s)V_{DC}G_p(s)}\right]\left[G_v(s)Z(s)V^*_L(s)\right] \tag{1}$$

As already discussed, in the proposed UPS system the purpose of PI voltage control $G_v(s)$ is to find the output voltage $V_L(s)$ closely to reference load voltage $V^*_L(s)$, and as well as minimizing the error to generate I^*_L signal for the PI controller as given in (2).

$$G_v(s) = K_P\left(1+\frac{1}{s\tau_r}\right), \tag{2}$$

where K_p is the proportional gain and τ_r is the reciprocal of the integrator gain. The function of current controller $G_c(s)$ is to equate I^*_L and I_L signals as close as possible and is given by

$$G_c(s) = K_P\left(1+\frac{1}{s\tau_r}\right), \tag{3}$$

The plant transfer function is given as

$$G_p(s) = \frac{1}{R(1+sT)}, \tag{4}$$

where $T = \frac{L}{R}$.

The transfer function for the inner loop of the system can be computed as

$$I_L(s) = \left[\frac{I^*_L(s)G_c(s)V_{DC}G_p(s) + I_U(s)G_p(s)}{1+G_c(s)V_{DC}G_p(s)}\right], \tag{5}$$

The proposed system open loop forward path gain of the inner loop is derived from (5) and (6) and given as

$$G_P(s)G_c(s) = \frac{V_{DC}K_P}{R\tau_r}\left(\frac{1+s\tau_r}{s(1+sT)}\right), \tag{6}$$

Eq. (6) is a second order equation and ideally it is in stable form regardless of the gain of PI controller K_p [13, 14].

Nonetheless, in practical scenarios, such kind of system become unstable before K_P is increased high enough to attain satisfactory control performance. Accordingly, an average value model is established which represents the proposed UPS system. The system, shown in Fig. 2(c), has accommodated the effect of transpose and sampling delays to the UPS system. The transpose delay is modeled using 1/Z block which is in series with the current controller and produced by the PWM process, whereas, the sampling delay is generated by a digital controller control system that is connected in series with current controller. The sampling delay is modeled using Z-transform theory [15] employing zero-order-hold (*ZOH*) element-block. The overall delay, both transport and sampling, is about 0.75 of the carrier frequency period for the current-control scheme of the proposed UPS system. The integral (K_i) and proportional (K_p) gains for PI current controller is taken as 110 and 10, respectively. Whereas the K_i and K_p gains for the PI voltage controller is taken as 100, and 0.01 per-unit, respectively. [16-19]. The Bode plot as shown in Fig. 2(d) is the stability analysis of the proposed UPS system under both condition, i.e. with and without transport and sampling delays; the figure shows that system is unconditionally stable at high frequency under both conditions. However, when these delays are considered, they cause the system to now roll off past the -180° stability limit at high frequencies.

To investigate the behavior of the proposed three-phase line-interactive UPS system during turning-on of an auxiliary load while powering the main load, consider the system presented in Fig. 2(b). For a better comparative analysis of the conventional and proposed line-interactive UPS systems, the transient and loading conditions of the proposed system are kept the same as those of the conventional UPS system that was discussed in a previous section. Here, the main load along with Load Transformer1 is on-line and the auxiliary load along with Load Transformer2 is off-line. As soon as $t=t_{Auxiliary\ Load}$, Load

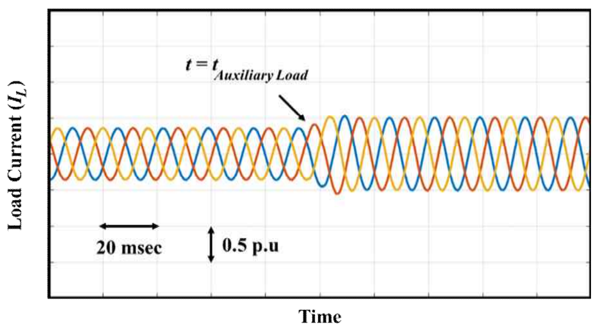


Fig. 3. Load currents (I_L) for the proposed line-interactive UPS system during switching-in of an auxiliary load while powering the main load

Table 1. Comparative analysis

Attribute	Conventional UPS System	Proposed UPS System
Power Application	Medium-High	Medium-High
Power Capacity	120%	110%
Efficiency	High	High
Power Regulating and Compensation	Yes	Yes
Cost, Size and Weight	Highest	Low
Time Required for Inverter or Compensation Mode	1-5 msec	Negligible
Inrush Current Possibility	Yes	No
Implemented Control Scheme	Complex	Simple

Transformer2 is attached to the inverter by means of a circuit breaker. As the auxiliary load is connected, the magnitude of the load current (I_L) increases sinusoidally as per the ratings of the auxiliary load and attains a prescribed value of 0.52 (p.u). Therefore, the possibility of generation of inrush current is eliminated, and the magnitude of the load current never go beyond the rated value at any stage. The behavior of the currents for the proposed line-interactive UPS system during switching-in of an auxiliary load while powering a main load is shown in Fig. 3. A comparative analysis of the conventional and proposed UPS system is given in Table 1.

3. Experimental Results

A small prototype laboratory-sized line-interactive UPS system is constructed to investigate the operation and performance of the proposed system during switching-in of an auxiliary load, meanwhile, powering the main load; the prototype is tested at different time instants of switching for the auxiliary load transformer. Table 2 shows the parameters of the proposed line-interactive UPS system.

The stationary frame is implemented by the DSP controller for the current control algorithm associated with the proposed UPS system. As discussed in section II (b) the proposed system has power components, such as, an inverter, isolation transformer, and two Δ-Y connected load transformers along with their respective loads. The DSP processor TMS320F28335 of Texas Instruments (TI) is used with 150MHz external clock to implement the proposed control scheme. However, the carrier period was 100 μsec. The overall delay, both transport and sampling, is about 0.75 of the carrier frequency period for the current-control scheme. The integral (K_i) and proportional (K_p) gains for PI current controller is taken as 110 and 10, respectively. Whereas the K_i and K_p gains for the PI voltage controller is taken as 100, and 0.01 per-unit, respectively. One 12 bit ADC channel is adopted for sampling of the load current and voltage calculated from the current and voltage sensors on the load side, respectively. A 10 KHz carrier frequency is used for commutation of the IGBTs

Table 2. System parameters

Parameter	Value
Utility/Grid	220 V, 60 Hz
DC Bus Voltage	365 V
Switching Frequency (f_s)	10 kHz
Load1	160 Ω, 21.5 mH
Load Transformer1	1 kVA, 220/220 (Δ-Y)
Load2	260 Ω
Load Transformer2	500 VA, 220/220 (Δ-Y)
Filter	L_f= 0.26 mH, C_f= 0.1 μF

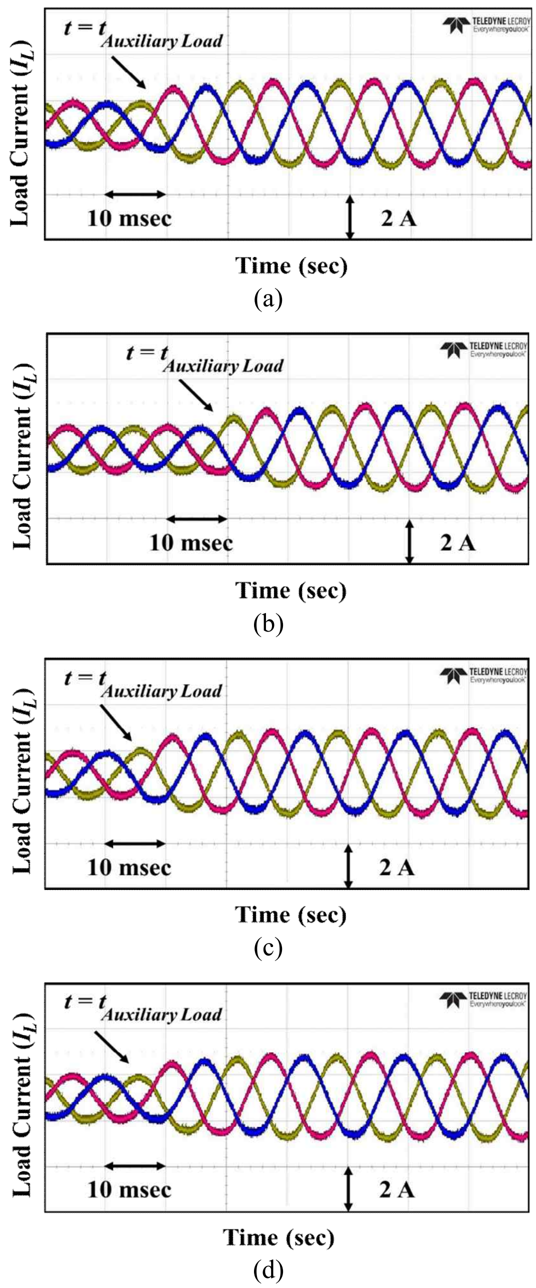


Fig. 4. Experimental results for the load currents (I_L) of the proposed line-interactive UPS system during switching-in of an auxiliary load at an angle of (a) 60 deg., (b) 120 deg., (c) 210 deg., and (d) 270 deg., of phase A, while powering the main load

switches of the inverter to generate PWM signal. A current control scheme is implemented in stationary frame of reference.

The peak of the inrush transient current depends on the operating principle and properties of the load transformer accompanied by the auxiliary load; the results are taken during the experiment to validate the response and operation of the proposed line-interactive UPS system during switching-in condition of the auxiliary load while supplying the power to the main load. The results are taken without changing the parameters of the load transformer; though the experiment is done for different switching-in conditions of the auxiliary load. The experimental results are shown in Fig. 4(a)-(d), they are taken for load currents (I_L) from the prototype when the auxiliary load was switched-in at angles of 60, 120, 240, and 210 degrees of phase A. during experiment the main load is powered by the proposed UPS system, when $t=t_{Auxiliary\ Load}$, the load transformer is connected through circuit breaker; the current is increased sinusoidally from 1 A to1.6 A, according to the rating of the of the auxiliary load.

The experimental results clearly show the effect of eliminating the inrush transient current; these results are even verified under different switching conditions of auxiliary loads.

4. Conclusion

The problem of inrush transient current available in conventional line-interactive UPS system during switching-in of an auxiliary load while powering the main load has been studied in this manuscript. A three-phase line-interactive UPS system is proposed that eliminated the probable inrush transient current during the event of switching-in of an auxiliary load with the aid of current regulated inverter. The power inverter of the proposed three-phase line-interactive UPS system adopted a current control algorithm which enabled it to increase the load current sinusoidally, meanwhile any inrush current generation was rejected. Moreover, the proposed UPS system contains single inverter, therefore, it has low cost, low size and less weight compared to the conventional UPS system. In the implemented control scheme the inner current control loop regulates the load current and has fast dynamics i.e., higher bandwidth (BW). However, the outer control loop controls the load voltage, generates reference signal for the inner loop and has slow dynamics i.e., low bandwidth (BW). Although this control strategy eliminates the inrush current phenomenon during switching-in of transformer-coupled loads however, the increase in the inverter output current is not quick but take a minimum of one half cycle to attain its rated value. This limits the adoption of the proposed system in the applications whose operation may get effected by the slow increase in the magnitude of inverter output current.

Acknowledgements

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