A three-phase off-line UPS system for transformer coupled loads

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Abstract: A number of critical load applications depend on a UPS system to uphold the normal operation. As soon as any disruption happens on the utility, an off-line UPS system starts supplying the power to the load to prevent blackout. Nonetheless, during this process, a substantial inrush current can be observed for the transformer-coupled loads. To avoid this inrush current, we propose an off-line UPS system based on a current regulated voltage source inverter. The inverter of the proposed UPS system uses a current control scheme executed in a stationary frame to regulate the load current and eliminates the likelihood of the inrush current. To endorse the performance of the proposed UPS system, we constructed a small prototype to obtain the experimental results.

Keywords: current controlled inverter, inrush current, off-line UPS, transformer-coupled loads

Classification: Circuits and modules for electronic instrumentation

References

[1] S. S. H. Bukhari, et al.: “An online UPS system that eliminates the inrush current phenomenon while feeding multiple load transformers,” IEEE Trans. Ind. Appl. 53 (2017) 1149 (DOI: 10.1109/TIA.2016.2622229).
[2] S. S. H. Bukhari and B.-I. Kwon: “A single-phase on-line UPS system for multiple load transformers,” IEICE Electron. Express 14 (2017) 20170050 (DOI: 10.1587/elex.14.20170050).
[3] C.-C. Yeh and M. D. Manjrekar: “A reconﬁgurable uninterruptible power supply system for multiple power quality applications,” IEEE Trans. Power Electron. 22 (2007) 1361 (DOI: 10.1109/TPEL.2007.900486).
[4] P. T. Cheng, et al.: “A transformer inrush mitigation method for series voltage sag compensators,” IEEE Trans. Power Electron. 22 (2007) 1890 (DOI: 10.1109/TPEL.2007.904186).
[5] S. B. Bekiarov and A. Emadi: “Uninterruptible power supplies: Classiﬁcation, operation, dynamics, and control,” IEEE Applied Power Electronics Conference and Exposition (2002) 1 (DOI: 10.1109/APEC.2002.989305).
[6] Y. H. Chen and P. T. Cheng: “An inrush current mitigation technique for the line-interactive uninterruptible power supply systems,” IEEE Trans. Ind. Appl.
46 (2010) 1498 (DOI: 10.1109/TIA.2010.2049817).

[7] K. P. Basu, et al.: “Elimination of inrush current in parallel transformers by sequential phase energization,” IEICE Electron. Express 4 (2007) 147 (DOI: 10.1587/elex.4.147).

[8] Y.-H. Chen, et al.: “An inrush mitigation technique of load transformers for the series voltage sag compensator,” IEEE Trans. Power Electron. 25 (2010) 2211 (DOI: 10.1109/TPEL.2010.2041793).

[9] S. S. H. Bukhari, et al.: “Elimination of the inrush current phenomenon associated with single-phase offline UPS systems,” Energies 9 (2016) 96 (DOI: 10.3390/en9020096).

[10] D. G. Holmes, et al.: “Optimized design of stationary frame three phase AC current regulators,” IEEE Trans. Power Electron. 24 (2009) 2417 (DOI: 10.1109/TPEL.2009.2029548).

1 Introduction

Power quality issues have become a fundamental concern for all kind of power consumers. These problems often disturb the process of manufacturing processes and lead to paraphernalia impairment [1, 2]. Because UPS systems are intended to automatically deliver backup power to critical loads, an off-line UPS system takes over the load completely within a quarter cycle whenever a disturbance occurs on the utility. The transference time of load depends on several factors including the time of the fault detection and the maneuver of switches [3, 4]. Although this span of time does not disrupt majority of the applications, it can cause severe problems by generating a large-magnitude inrush current for the transformer-coupled sensitive loads [5]. It is because of the fact that during this time, a flux offset is usually established, and as a consequence the load transformer installed before the load for isolation, goes into the saturation and starts drawing very large inrush currents. The size of such inrush current depends on some factors such as the switching instant and the magnetic properties of the load transformer [6]. Potential outcomes of the inrush current are the reduced line voltages and activation of a UPS system’s protection devices [7, 8]. In addition it can also cause the impairment of the sensitive load and shorten the life time of the load transformer.

The size of the inrush transient current that occurs when an off-line UPS system starts operating with a transformer-coupled sensitive load can be reduced by using some solutions offered by different scholars. Our literature analysis suggests that those solutions might have some disruptive effects on the UPS system. For example, adding the UPS voltage at suitable phase angles can lessen the amount of the inrush current but it can prolong the interruption. By means of resistors and reactors during the start of the UPS system could also be effective, but it will rise the dimensions of the system. Increasing the size of the load transformer to more than the rated flux density can also be an effective solution, but it will upturn the cost of the system. A flux offset compensation method to control the flux of the load transformer can be employed, but it complicates the overall control scheme for the UPS system [9].

We suggest that controlling the three-phase load currents can prevent the inrush current phenomenon. Thus, we here propose a three-phase off-line UPS system.
with a standard current regulated inverter which uses a current control strategy executed in a stationary frame. This control strategy works on newly developed three-phase control schemes which were actually intended for variable frequency motor control [10]. Furthermore, it is also perfectly apposite to control three-phase AC currents with any balanced load. This enables the proposed three-phase off-line UPS system to eliminate the inrush current phenomenon during the transition of a transformer-coupled sensitive load.

2 Operation and performance comparison

In this section, we explain the operating principles and performance of the conventional and proposed three-phase off-line UPS systems.

2.1 Conventional three-phase off-line UPS system

Fig. 1 shows a simple diagram of an off-line UPS system. As seen from the figure, it involves of a three-phase main switch whose responsibility is to connect the sensitive load to the utility, a battery that can be charged through any of the charging mechanisms (i.e., rectifier/charger), an inverter to feed the three-phase load from the backup power of the battery during abnormal utility condition and a three-phase alternate switch to connect the load to the inverter of the UPS system. The rating of the charger shown in the figure is about 20% (as it charges the battery only), and the power rating of the three-phase inverter is about 100% (because it delivers the rated power to the load). During normal utility, main switch bypasses the inverter, and the load receives power from the utility. The UPS system is thus believed to be in normal mode. In the meantime, the battery is being charged using the provided rectifier. On the other hand, as soon as the utility goes through any disruption, main switch opens, and the alternate switch energizes to connect the load to the inverter to supply the backup power. The system is now believed to be in inverter mode. This transfer of load takes some time which ranges from 4–20 msec, reliant on the fault recognition and the load transferring devices. Major advantages that a three-phase off-line UPS system offers are: high efficiency, small size, simple design, and low cost. Conversely, some of the disadvantages accompanying with this system are the absence of isolation of load from the utility and the power supplied to the load is not regulated; thus, the load is not protected from any transient happening on the utility. For those reasons, the conventional three-phase off-line UPS topology is generally adopted for low-power applications. Additional drawbacks include performance issues with nonlinear loads and the transfer switching time interval, which is usually about a quarter of the cycle as discussed before.

Intended for the satisfactory isolation of sensitive loads from the utility, a load transformer is commonly mounted before the load, as shown in Fig. 1. However, installing the three-phase load transformer for isolation purposes can produce a severe magnitude of inrush current in the course of the transference of load from the utility to the UPS system. Fig. 2 illustrates the performance of a conventional three-phase off-line UPS topology during such a condition. From the figure, it can be observed that, as soon as the transfer of load from the utility to the inverter takes
place, the load current attains a peak of 22.2 A, which is more than five times higher than the desired value.

2.2 Proposed three-phase off-line UPS system

The basic operating principle of the proposed three-phase UPS system is analogous to that of the conventional three-phase off-line UPS topology shown in Fig. 1. However, the proposed UPS system is based on a current regulated voltage source inverter instead of the conventional PWM voltage source inverter. The three-phase inverter in this case uses one of the previously presented current regulating schemes executed in a stationary frame. That allows it to control the load current for the inverter, completely eliminating the possibility of generating inrush current. Because the proposed three-phase UPS topology does not require any additional hardware components, it offers the advantages of high efficiency, small size, simple design, and low cost, similar to those of the conventional topology with a load transformer. However, since the proposed topology provides complete elimination of inrush currents along with an acceptable isolation of load and the inverter of the UPS system, it can be employed for three-phase high-power loading applications assuming that the rectifier is connected to the utility through converter transformer. This approach is also possible for a typical single-phase off-line topology. However, the magnitude of inrush current is always higher in the case of three-phase (Δ-Y connected) transformer-coupled loads compared to the case operating under single-phase power supply. The increase in the magnitude is due to the electrical connections of the primary of the load transformer.

The performance of the proposed system depends on an enhanced three-phase PI current regulator implemented in stationary frame adopted for the inverter, which is perfectly apposite for directly regulating three-phase AC currents with and without associated EMF (i.e., motor loads) [10]. This current control is simple and easy to execute. The transfer function of the proposed three-phase UPS system is specified by:
where $I(s)$ is the rated load current, $I^*(s)$ is the reference signal, $G_c(s)$ is the transfer function of the PI controller, $H(s)$ is the plant transfer function.

The performance of the PI controller while dealing with DC currents is excellent since the gains of the controller under such a condition can be increased without any constraint. However, while operating with AC currents, the performance of the PI controller is less satisfactory. It is because of the fact that the operation of controller is always influenced by transport and sampling delays. These delays restrict the PI controller to attain zero steady state error and track the reference commanded signal while achieving high possible gains.

The average value model representations of the proposed system while considering the effects of sampling and transport delays is shown in Fig. 3, where $V_{DC}$ is the forward gain of the amplifier used for the PWM modulator, $E_c(s)$ is the error obtained through the comparison of controlled and reference signals, and $Z0H$ and $1/Z$ blocks are used to model transport and sampling delays respectively.

![Fig. 3. Average value model representation for the proposed UPS system.](image)

Fig. 4 shows the performance of the proposed three-phase off-line UPS system in the course of the transition of load from the utility to the inverter. From the figure it can be seen that the load current remains constant and never exceeds the rated load current i.e., 4 A, at any point during the load shifting process.

![Fig. 4. Load currents for the proposed three-phase off-line UPS system during the transition of load from utility to inverter.](image)

### 3 Experimental results

In order to confirm the effectiveness of the proposed three-phase off-line UPS system, we built an experimental setup with the parameters given in Table I.

| Parameter               | Value                |
|-------------------------|----------------------|
| Utility                 | 220 V, 60 Hz         |
| Inverter Switching Frequency | 10 kHz           |
| DC Bus Voltage         | 365 V                |
| Transformer Ratings    | 500 VA, 220/220 V    |
| Load Resistance ($R_L$) | $R_L = 40 \Omega$ and $L_L = 10.75 \text{ mH}$ |
| Filter Inductance ($L_f$) | 0.265 mH          |
Custom made DSP control board with DSP TMS320F28335 from Texas instrument is used to implement the proposed control strategy. Current sensors are used to feed back the current via 12-bit ADC interface available at the DSP board. PI regulators are implemented to regulate the load currents for a passive RL load according to the commanded currents.

During the normal operating mode of the proposed off-line UPS system, the load is provided current from the utility through main switch. However, the inverter remains off. Moreover, as the utility gets off i.e., blackout occurs, the main switch gets opened and the alternate switch gets closed. The load is then supplied current from the inverter and the system is believed to be in inverter mode. Fig. 5 shows the experimental waveforms of the proposed off-line UPS system during inverter mode. Fig. 5(a) shows the utility currents. However, inverter and load currents are shown in Fig. 5(b) and (c) respectively. From the experimental results, it is clear that our proposed system eliminates the possibility of generating an inrush current for a transformer-coupled sensitive load during the transition of load.

4 Conclusions
In this paper, we proposed a new three-phase off-line UPS system based on a current regulated inverter to eliminate the inrush current associated with transformer-coupled load. Furthermore, we have also shown that our proposed system offers advantages similar to those of the conventional topology. Finally, we also verified the operation of the proposed UPS system by showing experimental results.

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