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Application of a Synchronization System for Control of Ground to Airplane Power Transfers

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ABSTRACT

Recent advances in the development of a more robust synchronization strategy has made it viable to propose a control system for a no-break power transfer in aerospace applications. The proposed system constitutes a combination of a multirate phase locked loop with a positive sequence detector. Synchronization to the positive sequence component, in the presence of unbalanced loads, minimizes the circulating real and reactive power. The amplitude, frequency, and phase of the airplane power source are made available. The no-break control system automatically sets the ground power unit to the frequency and phase of the aircraft power unit and adjusts its amplitude to the required level. The relays are then closed and the ground power unit is connected to the airplane load. The amplitude information is provided by an automatic gain control (AGC) loop. The AGC loop ensures that the multirate phase locked loop is insensitive to disturbances, noise, and harmonic distortion present on power lines. The experimental results indicate a 60 dB immunity to impulse noise and harmonic contamination as well as a 20 dB dynamic range.

INTRODUCTION

Advances in new synchronization approaches have initiated a reevaluation of the electrical power quality for ground to airplane transfer. The advances provide an uninterrupted power flow to the electrical equipments onboard the airplane. This, as a result, contributes to passengers' contentment and peace of mind as well as the power system performance of the aircraft. Furthermore, the amount of maintenance for power transfer can be reduced.

Presently the application of a ground power unit (GPU) for delivery of electric power to airplanes during stopovers in airports is well established. The need for GPU is mainly due to the regulations imposed by the airports. The regulations mandate a reduction in the acoustic noise and air pollution generated by the airplanes and their auxiliary power unit (APU).

Solid-state converters and rotating electrical generators are employed for the GPU power plant. The solid-state approach is employed in numerous commercial products [1] and can be easily reconfigured to provide a wide array of output ratings. Typically lower cost and maintenance, and high reliability and efficiency favor the solid-state approach.

Figure 1 shows a typical aircraft power distribution system along with the main points of regulation (POR) [2]. Two PORs, one at the output of the GPU and the other at the aircraft generating source are of interest in terms of the power transfer to the airplane. In general, there are two types of AC power sources aboard aircrafts: (a) a 400 Hz constant frequency (*CF*) in addition to (b) a wide-range variable frequency (*VF*) [2]. The wide-range is due to wide speed variations on large turbofan engines as compared to a turboprop. The GPU electric power is set to 400 Hz in order to match the *CF*. On the other hand, the frequency range for *VF* is 360-800 Hz [2], [3].

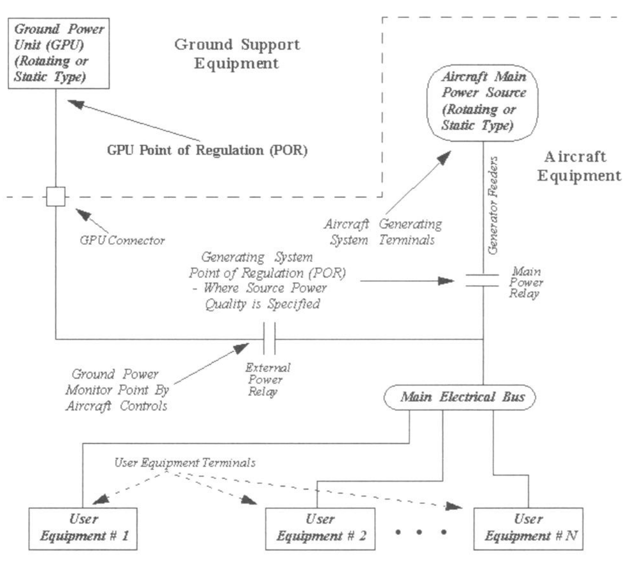

Figure 1: Typical aircraft electrical power distribution.

The main power sources onboard some of newly designed airplanes such as the Boeing 777 are designed to generate 400 Hz electric power. Each generator is integrated with a constant speed drive. This combination is referred to as an integrated drive generator (IDG). The generated electric power is regulated at 400 Hz. The backup system is directly connected to the main engine gearbox with no speed regulation. This leads to a *VF* electric power generation. The *VF* power is converted to a 400 Hz *CF* in order to make it compatible with the main power source of the aircraft [4].

One approach to transfer electric power to the airplane is to disconnect all the power sources from the loads for a short time and then connect the desired power source. Unfortunately, a momentary power loss could damage onboard equipment. The other disadvantage is due to delay times attributed to the openings or closures of the relays [5]. If the relay is closed too early there will be a momentarily short that leads to circulating currents. Another approach is a no-break power transfer. The no-break power transfer offers no load power discontinuity by momentarily paralleling the GPU and the power unit of the airplane. During this process, both GPU and onboard power unit are connected while supplying power to the loads. Then one of the power sources is disconnected from the loads. Therefore, there is no power loss and the delay times attributed to relay opening/closure becomes insignificant [5]. Furthermore, paralleling requires precise synchronization between the sources, otherwise, real or reactive currents will circulate [5]. Typically, synchronization would entail knowledge about the frequency, voltage, and phase angle of the power source.

The limitations of the available synchronization methods and the various *CF* or *VF* electric power configurations indicate a niche for a universal, flexible, simple, streamlined approach to connecting sources. Consequently, this paper proposes a synchronization module consisting of a multirate phase locked loop and a real-time positive sequence detector. The voltage generated by the generating source is a positive sequence component. Hence, synchronization to this component is desired. Unfortunately, negative and zero components appear due to unbalanced loads. Hence, a real-time positive sequence component must be extracted for synchronization purposes.

The next section provides a brief description of the existing methods of synchronization. A discussion of the proposed multirate phase locked loop/positive sequence detection synchronization method as well as the overall approach of the proposed method is presented in the subsequent section. Finally, conclusions are provided.

EXISITING METHODS

This section provides a summary of existing methods that address the no-break power transfer in the aerospace industry.

CONTROL METHOD FOR 400 HZ GROUND POWER UNITS – A new control method for a 400 Hz GPU for airplanes is presented in [6]. In this method the frequency of the aircraft is considered to be 400 Hz for an IDG constant speed generator. Figure 2 shows an overview of this method where the 50 Hz input AC mains signal is filtered, rectified, and inverted into an AC output at 400 Hz. This output voltage is then filtered and connected to the airplane via a 100 meter cable.

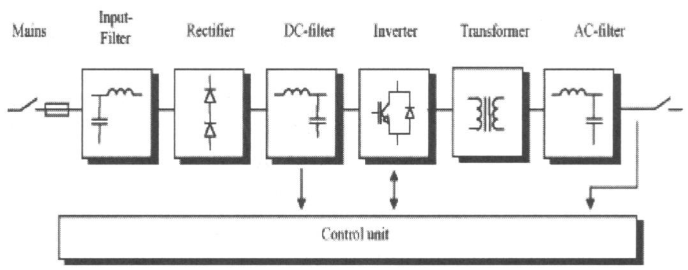

Figure 2: Block diagram illustrating the control method for a 400 Hz. GPU [6].

The control strategy involves a vector control of the GPU based on the Park transformation [6]. A voltage controller provides an input to a modulator, which controls the inverter. The synchronization between the GPU and the airplane is based on a single-phase system consideration and is shown in Figure 3. The effects of the load are neglected, hence, contamination of the synchronization information by the presence of impulse noise, harmonics and notch disturbances, on the main power bus of the airplane, is not considered. Further, the synchronization information provided to the control unit is not capable of providing the phase difference between the two sources and hence power transfer leads to transient currents flowing into/out of the GPU. This leads to circulating real and reactive powers.

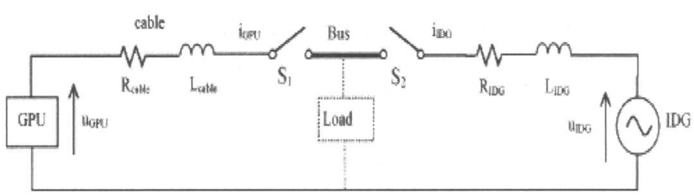

Figure 3: Single-phase model [6].

DIGITALLY CONTROLLED UPS FOR AIRPORT INSTALLATIONS – A digitally controlled uninterruptible power supply (UPS) with a three-phase, 400 Hz output voltage is designed and prototyped. The prototype is intended to be used as the GPU at airports. The UPS concept, which has been used for power sensitive loads such as personal computers (PCs) and medical equipment, has been extended to include power delivery to airplanes. Figure 4 shows a simplified schematic of this method [7].

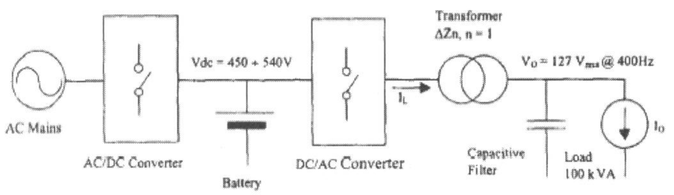

Figure 4: Schematic of the digitally controlled UPS [7].

This method is similar to the previous method with the difference that the DC bus capacitor is replaced with a bank of energy storage devices such as batteries. The intention is to provide a no-break UPS where the load is supplied by a PWM-controlled DC/AC converter. In either method, it is assumed that at the instant of power transfer, the transients and circulating currents are minimal and are compensated quickly enough by the GPU. No mismatch between the two sources is considered.

PROPOSED METHOD

A new synchronization approach is proposed in this paper in order to overcome the shortcomings of the existing methods. The shortcomings are caused specifically by the lack of accurate synchronization information; frequency, amplitude, and phase angle of the electric power onboard the airplane. The proposed method combines a multirate phase locked loop with a positive sequence detector. In this section a discussion on the multirate phase locked loop and the sequence detector is provided followed by a detailed description of the overall approach.

MULTIRATE PHASE LOCKED LOOP – A digital signal processing system based on a multirate phase locked loop (MPLL) for applications in AC utility network signals in power systems and power electronics is presented in [8], [9]. This system provides synchronization information in the presence of severe disturbances on power lines and a time varying signal frequency and fundamental component amplitude.

Fig. 5 shows a block diagram of the MPLL. A bandpass digital filter is used to attenuate the disturbances and any harmonics on the line. The resultant fundamental component of the input signal is provided to a downsampler block. An amplitude detector in combination with an automatic gain control (AGC) is used to make the controller response insensitive to changes in the input signal magnitude. The output of the controller is an error signal. A nonzero error signal, depending on its polarity, decreases or increases the sampling frequency of an analog-to-digital converter (ADC) and also ensures that the output fundamental component signal remains in phase with the input fundamental component signal.

The MPLL operates at two sample rates. These sample rates are referred to as fast (f_s) and slow (f_{sys}) where f_{sys} is equal to the input signal frequency. The f_s and f_{sys} are related to each other by the number of samples per cycle (N) such that

$$N = \frac{f_s}{f_{sys}} \quad . \qquad (1)$$

The sampling rate of the ADC is set by the fast sample rate (f_s).

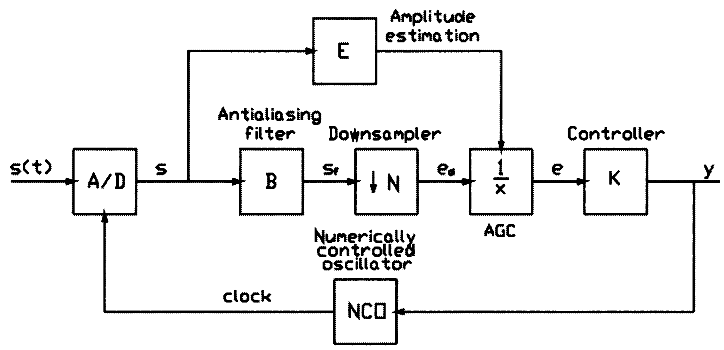

Figure 5: MPLL block diagram [8].

The MPLL is implemented on a microprocessor platform [10]. The implementation results indicate a 60 dB immunity to impulse noise and harmonic contamination as well as a 20 dB dynamic range. These results also indicate that the performance of the MPLL is restricted to conventional AC utility network applications where the frequency is 50 or 60 Hz; the MPLL frequency range is between 48 to 72 Hz. The restriction on maximum frequency is mainly imposed by the minimum timer setting on the microprocessor [10].

Figure 6 depicts a network voltage with notch disturbances and noise as well as a resultant generated square waveform aligned to the zero-crossings of the network voltage.

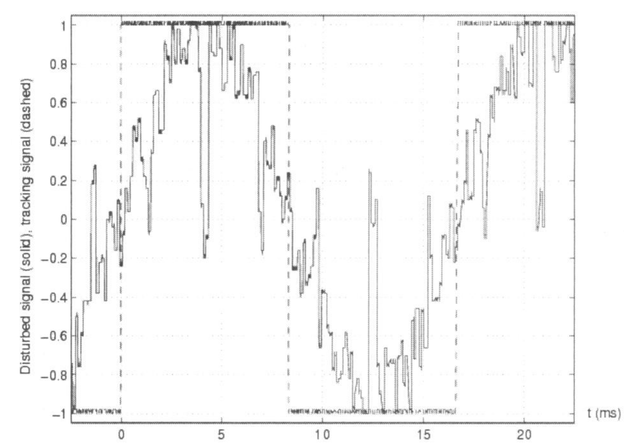

Figure 6: Disturbed network voltage and the resultant rectangular synchronization waveform aligned with zero-crossings [8].

POSITIVE SEQUENCE DETECTOR – Sequence components are employed in three-phase power networks to detect system unbalances. An unbalanced system leads to positive, negative, and zero sequence components while a balanced system produces only a positive sequence component. The positive sequence is the component that represents the main characteristics of the three-phase electric power. In fact, this is the original signal generated at the source and is the correct signal to employ for synchronization purposes.

The conventional symmetrical component method is a general mathematical method given in [11]. The real-time sequence detector is based on this mathematical approach and is described in [12]. This method is capable of providing sequence components from the three-phase electric power even when the frequency varies. This method continuously alters the coefficients of the transfer function as the frequency changes. The detailed mathematical proof behind this method is found in [13]. The per-unit equation for the positive sequence component is given in [13] as

$$3\cdot V_{Pos}(\beta) = 1 + P_b\cdot e^{j\cdot\frac{4\cdot\pi}{3}} - Z_b\cdot e^{j\cdot\left(\frac{4\cdot\pi}{3}-\beta\right)} - P_c\cdot e^{j\cdot\frac{2\cdot\pi}{3}} + Z_c\cdot e^{j\cdot\left(\frac{2\cdot\pi}{3}-\beta\right)} \tag{2}$$

where

$$p_b = \frac{1}{\tan\left(\frac{\pi}{6}+\beta\right)\cdot\cos\left(\frac{\pi}{6}\right) - \sin\left(\frac{\pi}{6}\right)},$$

$$p_c = \frac{1}{\sin\left(\frac{\pi}{6}\right) - \tan\left(\frac{\pi}{6}-\beta\right)\cdot\cos\left(\frac{\pi}{6}\right)},$$

$$Z_b = \frac{1}{\sin\left(\frac{\pi}{6}+\beta\right) - \cos\left(\frac{\pi}{6}+\beta\right)\tan\left(\frac{\pi}{6}\right)},$$

$$Z_b = \frac{1}{\cos\left(\frac{\pi}{6}-\beta\right)\cdot\tan\left(\frac{\pi}{6}\right) - \sin\left(\frac{\pi}{6}-\beta\right)},$$

$$\beta = \frac{2\pi f_{sys}}{f_s},$$

and f_s and f_{sys} are the sampling and the base input signal frequencies respectively.

Figure 7 illustrates the frequency response of this system. The response characteristics are similar to a highpass filter below the Nyquist sampling frequency.

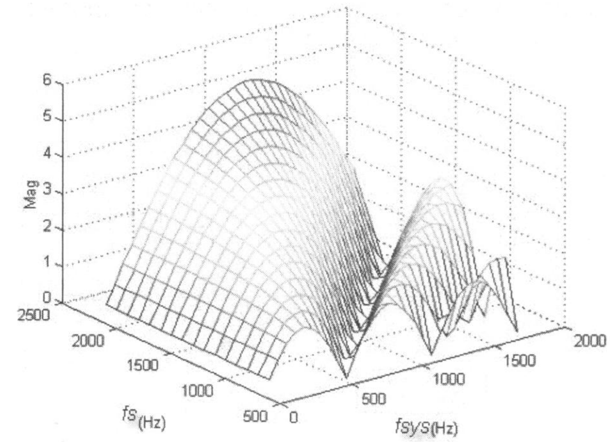

Figure 7: Frequency response of positive sequence detector [13].

Input signals and the related outputs are shown in Figure 8(a) and 8(b) respectively. From *0* to t_2 the input is a symmetrical positive sequence and the magnitude changes at t_1. At t_2 and t_3, only zero and negative sequences are present respectively. Finally, at t_4, only the positive sequence reappears.

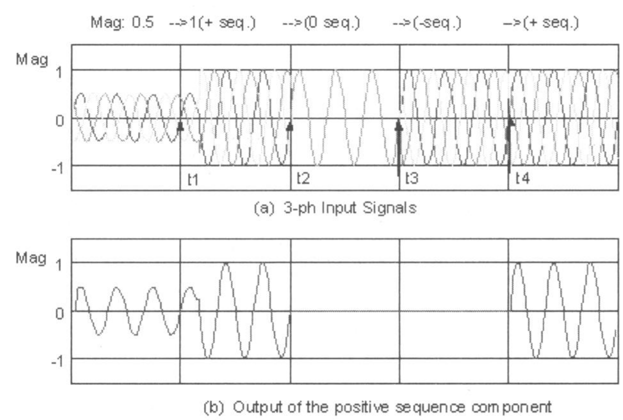

Figure 8: Positive sequence outputs for different inputs [13].

Combining the MPLL and Positive Sequence Detector - The MPLL is combined with the positive sequence detector to make a complete synchronization block. The implementation of the MPLL and positive sequence detector on a FPGA platform [14] is required in order to extend the frequency bandwidth and thereby satisfy the aerospace requirements [3].

Figure 9 depicts the MPLL and the positive sequence detector where equation (2) represents the positive sequence detector output signal. Any variation of the input signal frequency (f_{sys}) is compensated by a change in f_s in order to maintain a constant *N*, as equation (1). Also, an additional signal denoted as the zero-crossing reference (*ZCR*) signal is implemented. The *ZCR* signal indicates the positive zero-crossing of the input signal, hence, a comparison of the *ZCR* signal from the GPU with the *ZCR* signal from the electric power onboard the airplane results in a phase difference. In order to force the phase difference value to zero the phase of the GPU is adjusted accordingly. In addition, the proposed system also provides access to the fundamental component voltage magnitude and frequency.

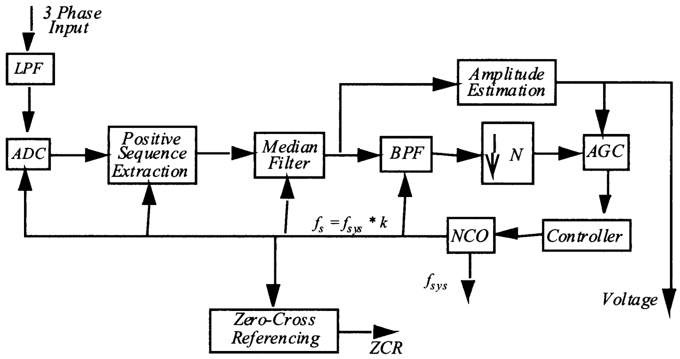

Figure 9: Combined MPLL with positive sequence detector constituting the synchronization block.

OVERALL PROPOSED METHOD FOR GROUND TO AIRPLANE POWER TRANSFER – Figure 10 illustrates the overall proposed method where the detailed content of the synchronization block is provided in Figure 9.

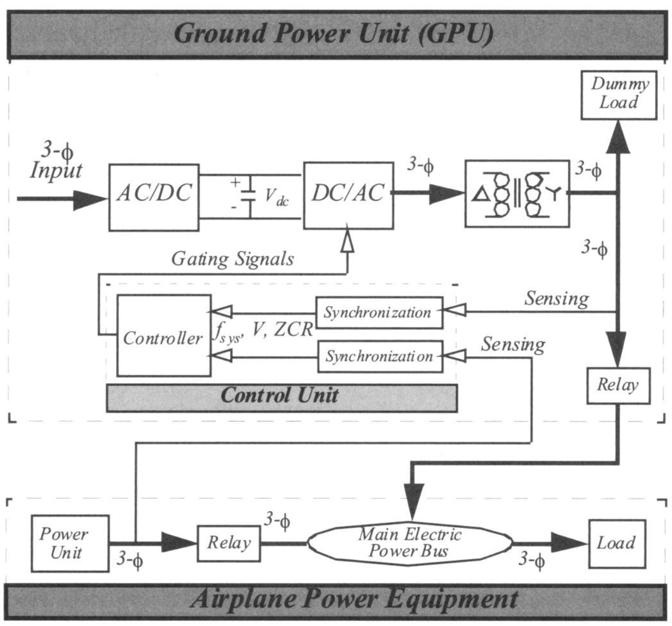

Figure 10: Overall proposed method for ground to airplane power transfer.

The main power plant is comprised of an AC-to-DC rectifier, controlled DC-to-AC inverter, an isolation transformer, and a dummy load. The control unit is located on the GPU and senses the voltages of the power generated onboard the airplane and the GPU. The voltage, frequency, and phase of the GPU are controlled by the gating signals determined by the control unit. The proposed concept takes into account the following two cases: (a) the GPU takes control over power delivery to the main electric power onboard the airplane; (b) the power unit of the airplane takes control.

Transfer of power delivery to GPU – During this operation, the main electric power onboard the airplane is provided by the onboard power unit. It is desired to transfer the supply of the electric power to the GPU. Hence, upon connection of the GPU to the airplane the event sequence that transpires is as follows:

- The power generated by the power unit onboard the airplane is sensed and its characteristics such as frequency (f_{sys}), voltage (V), and phase (ZCR) are determined by the control unit located on the GPU.
- The output power of the GPU is adjusted until it matches the power onboard the airplane. During this phase, the controller gradually sets the gating signals of the inverter and at the same time senses and determines the characteristics of the power generated by the synchronization block until a close match is obtained.
- The GPU relay is closed followed by the opening of the onboard relay. The airplane crew is then informed of the power transfer completion via a control signal and the onboard power unit is shut down.

Transfer of power delivery to the onboard power unit – In this case the GPU is providing power to the airplane and it is desired to switch over to the onboard power unit of the airplane. Therefore, upon activating the onboard power unit, the following sequence of events transpires:

- The onboard power unit is activated and the generated power is sensed. Sensing continues and the synchronization block provides the values of the generated voltage and frequency to the controller unit. The controller unit compares these values to a set of predefined parameters until a desired operating point is reached.
- The phase difference is determined by comparing the ZCRs from the GPU and the onboard power unit. Based on the onboard power generated and the phase difference, the output of the GPU is gradually adjusted until a close match is obtained.
- The onboard relay is closed followed by opening of the GPU relay. The GPU is then shut down and disconnected from the airplane.

CONCLUSION

The combination of a new multirate phase locked loop (MPLL) synchronization method along with a real-time positive sequence detector is proposed. This system allows for a bumpless transfer of power between ground and the main electric power unit of the airplane. Both MPLL and positive sequence methods are described. The overall system is explained and the event sequences for two specific power transfer cases are provided. The proposed control method is frequency adaptive and is immune to disturbances. The frequency, amplitude, and relative phase of the fundamental component can be extracted. The proposed implementation is capable of automatically synchronizing the GPU and main electric power onboard the airplane using positive sequence information. This results in a minimization of the circulating real and reactive powers during a power transfer.

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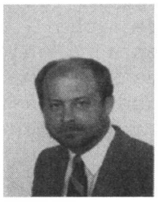

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