Modeling and Simulation of a 24-pulse Transformer Rectifier Unit for More Electric Aircraft Power System

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***Abstract* – This paper presents a study on a three-phase 24-pulse Transformer Rectifier Unit (TRU) for use in aircraft electric power system. Four three-phase systems with 15º, 30º, 45º, and 60º phase shifts are obtained by interconnection of conventional transformers in zig-zag configuration. The system is modeled in details using Simulink (SimPowerSystems). Simulation results are presented and the obtained performance is compared with those of a 12-pulse TRU.**

I. INTRODUCTION

Multi-pulse rectifiers are being increasingly used in more electric aircraft (MEA) applications where high power quality specifications are required, in particular low input harmonic contents. Most popular TRU systems include 12-pulse and 24-pulse topologies that can satisfy harmonic requirements set by RTCA standards [1], [2]. Also, these multi-pulse rectifiers can provide high power factor and thus the reactive power requirement is reduced.

When 12-pulse rectifiers are used, passive or active filters are usually required to reduce the input line current THD to an acceptable level. The additional volume and weight brought by the filters to the system can counterbalance the advantages. On the other hand, 24-pulse rectifiers can meet the harmonic requirements without additional filters so that their volume and weight can be less than the combination of 12-pulse converters and filters.

The purpose of this paper is to present a study on a three-phase 24-pulse transformer-rectifier unit (TRU) for use in more electric aircraft electric power system. Four three-phase secondaries with 15º, 30º, 45º, and 60º phase shifts are obtained by interconnection of conventional transformers in zigzag configuration. The system is modeled by using three-phase transformer Simulink models available in SimPowerSystems. Simulation results obtained for various load conditions are presented and discussed. They are then compared with those obtained with an equivalent 12-pulse system.

II. DESCRIPTION OF 12-PULSE AND 24-PULSE TRU

Multi-pulse rectifiers use various pulse multiplication schemes to produce the desired pulse number in the input currents and the output voltages [3], [4]. The electromagnetic device needed to create the different phase shifts can be multi-winding transformer or auto-transformer or a combination of three-phase and single phase transformers. The windings are then connected together following particular configuration to obtain the desired configuration.

A. 12-pulse TRU

Fig. 1 shows a block diagram of a 12-pulse TRU using an input three-phase transformer with two secondaries connected in Y and Δ with unit transformation ratio.

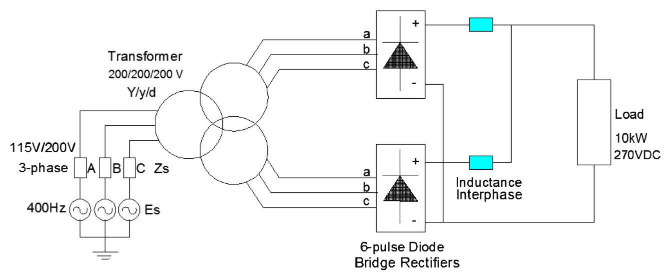
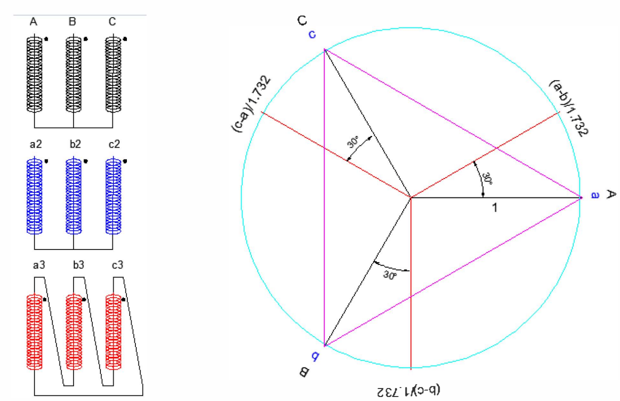


Fig. 1 Block diagram of a 12-pulse TRU.

Two three-phase output voltage systems have the same amplitude and 30º phase shift between them. The required phase shifts are obtained by connecting the secondaries in Y and Δ configurations. Fig. 2 shows the 12-pulse transformer winding connections and a phasor diagram representing the six-phase output voltages.



(a) (b)

Fig. 2 12-pulse input transformer.
(a) Windings connection. (b) Phasor diagram.

Two six-pulse diode bridges are used to convert secondary three-phase voltages to two dc voltages with 2400 Hz ripple. The dc outputs are connected in parallel to the load, through interphase inductors, to provide a dc voltage having 4800 Hz ripple. The interphase inductors are used to limit the circulating current between secondaries and to reduce the output ripple.

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B. 24-pulse TRU

Fig. 3 shows a block diagram of a 24-pulse TRU using an input three-phase transformer with four secondaries.

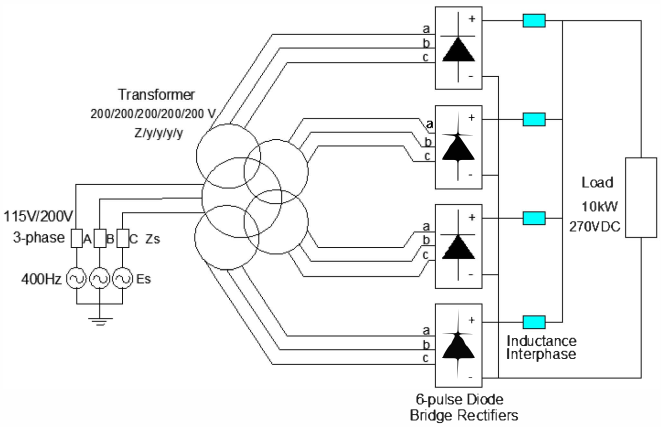
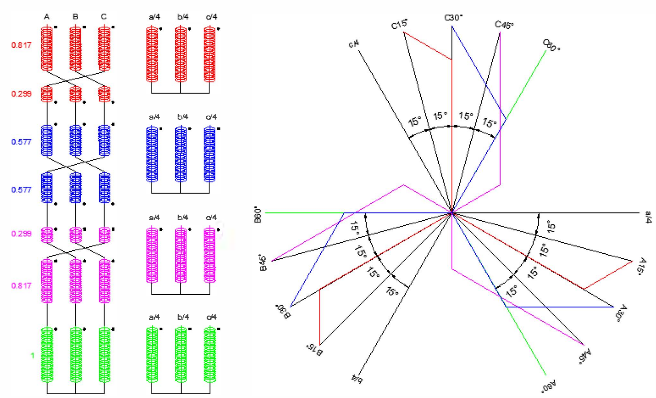


Fig. 3 Block diagram of a 24-pulse TRU.

The three-phase output voltages provided by four secondaries have the same amplitude and 15° phase shift between them. The required phase shifts are obtained by connecting the primary windings in zigzag configuration. Fig. 4 shows the 24-pulse transformer windings connection and a phasor diagram representing the twelve-phase voltage system at the transformer output.



(a) (b)

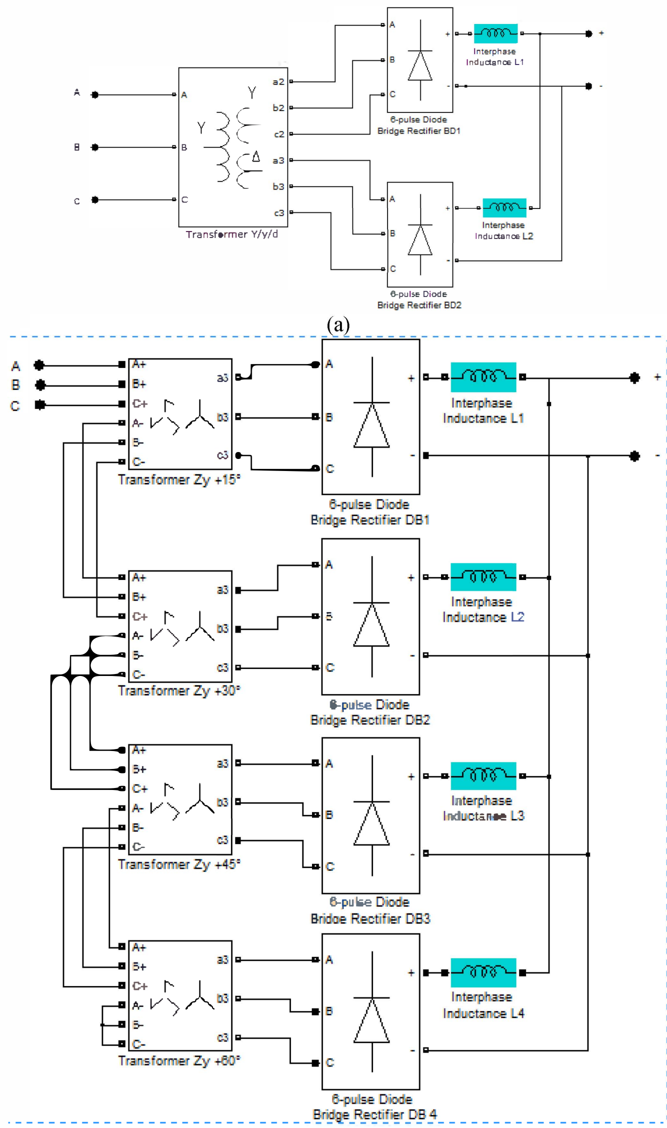
Fig. 4 24-pulse input transformer.
(a) Windings connection. (b) Phasor diagram.

Four six-pulse diode bridges are used to convert three-phase output voltages to four dc voltages with 2400 Hz ripple. The four dc outputs are connected in parallel to the load, through interphase inductors, to provide a dc voltage having 9600 Hz ripple. The interphase inductors are used to limit the circulating current between secondaries and to reduce the output ripple.

III. MODELING 12-PULSE AND 24-PULSE TRU

The above mentioned 12-pulse and 24-pulse TRU were modeled and simulated by using SimPowerSystems, a Simulink's simulation tool, since all the needed models are available and ready to use.

Fig. 6 shows Simulink diagrams which represent the 12-pulse and 24-pulse TRU under consideration.



(a)

(b)

Fig. 5 Simulink diagrams representing models of studied TRU.
(a) 12-pulse TRU. (b) 24-pulse TRU

The TRU are operating under identical conditions. The AC power source is a 115V/200V 400 Hz three-phase system. The rated DC output voltage is 270 VDC. A 10 kW resistive load is connected to the output of the rectifier. The rated DC output current is thus 37 A.

In the 12-pulse TRU, a Y/Y/Δ 200V/200V/200V 400 Hz input transformer is used.

In the 24-pulse TRU, four Z/Y 50V/200V 400 Hz input transformers are used. The second set of primary windings are interconnected in zigzag to produce the required phase shifts.

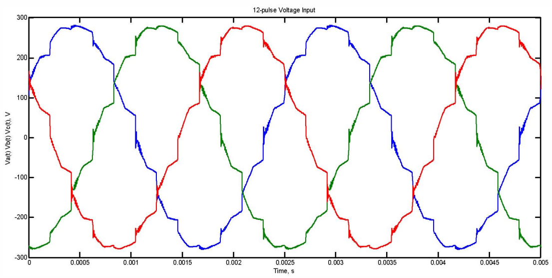
The interphase inductor value has been chosen to limit the output current ripple to 10% of its rated value. This value is 136.7 µH for 12-pulse TRU and 68.35 µH for 24-pulse TRU.

IV. SIMULATION RESULTS

The Simulink diagrams representing the TRU models were simulated using various load conditions, from 50% to 100% of rated value (10 kW).

A. Input voltages and currents

The voltage and current waveforms for both TRU are recorded and shown in Fig. 6 and Fig. 7 for comparison purpose.



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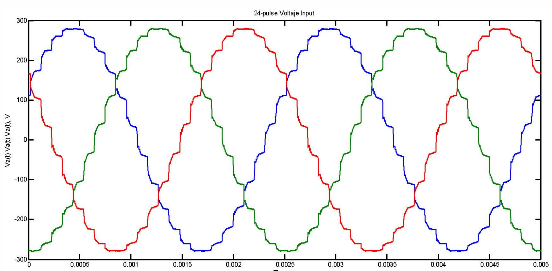
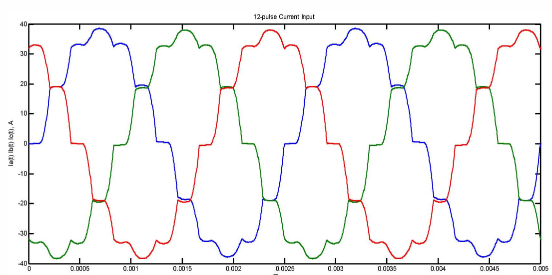


(b)

Fig. 6 Comparison of line-neutral AC input voltages.
(a) 12-pulse TRU. (b) 24-pulse TRU.



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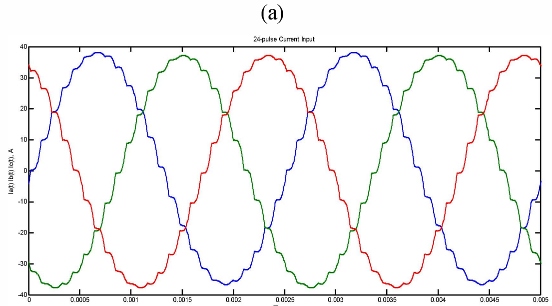
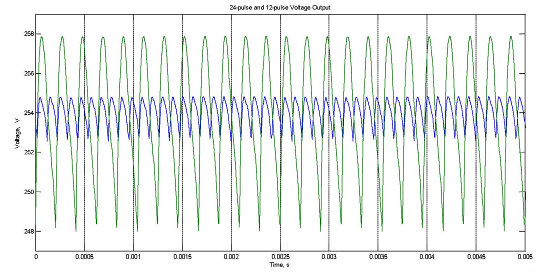


(b)

Fig. 7 Comparison of AC input current waveforms.
(a) 12-pulse TRU. (b) 24-pulse TRU.

DC output voltage and current waveforms are shown in Fig. 8. We can note the reduced ripple on voltage and current waveforms obtained with 24-pulse TRU.



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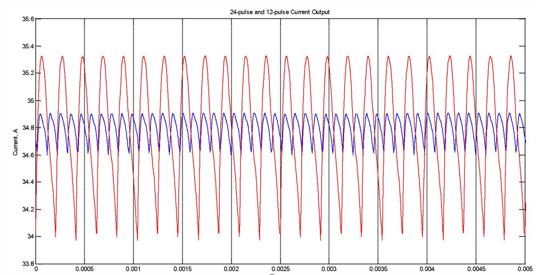
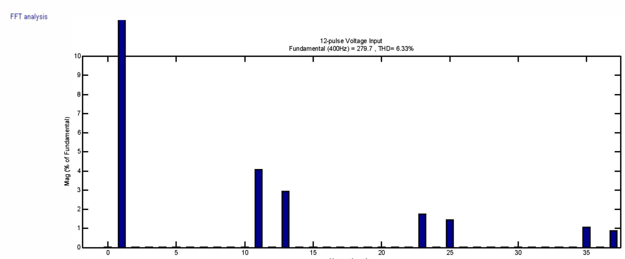


(b)

Fig. 8 DC output waveforms.
(a) Voltage waveforms (Green 12-pulse – Blue 24-pulse).
(b) Current waveforms (Red 12-pulse – Blue 24-pulse).

B. Input voltage harmonics

The AC input voltage spectra for both TRU are shown in Fig. 9.



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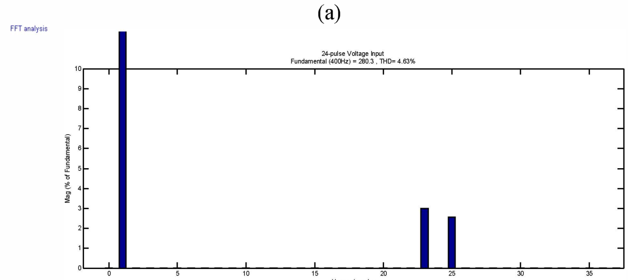
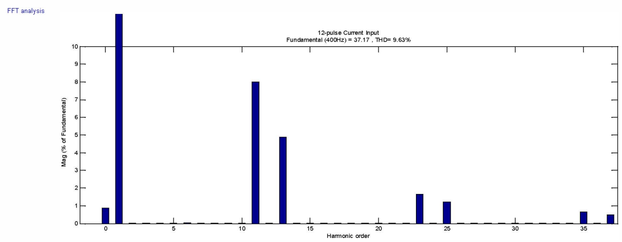


(b)

Fig. 9 Comparison of AC input voltage spectra.
(a) 12-pulse TRU. (b) 24-pulse TRU.

We can note that the first harmonics of 24-pulse TRU waveforms start at 23 and 25 by contrast with 12-pulse TRU harmonics which start at 11 and 13.

Fig. 10 shows the AC input current spectra obtained with both TRU. We can have the same remarks regarding the first harmonics of the two waveforms



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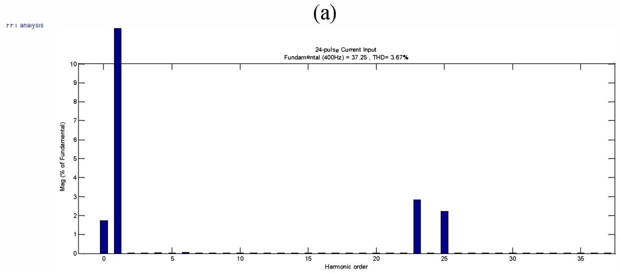


(b)

Fig. 11 Comparison of AC input current spectra.
(a) 12-pulse TRU. (b) 24-pulse TRU.

The harmonic contents of the 24-pulse TRU increase with the load as shown in Table I. The maximum value of THD (3.67%) is obtained at full load.

TABLE I
24-PULSE TRU INPUT CURRENT HARMONICS

Load (%)	THDI (%)	I_{23} (I_1%)	I_{25} (I_1%)
50%	2.43	1.81	1.45
60%	2.79	2.13	1.67
70%	3.07	2.36	1.85
80%	3.32	2.56	2.00
90%	3.50	2.71	2.11
100%	3.67	2.84	2.21

There are no 11th and 13th harmonics in the input current. The maximum value of 23rd and 25th current harmonics are respectively 2.84% and 2.21%. These values are lower than the 3% value set by RTCA (Table II).

TABLE II
CURRENT HARMONIC LIMITS FOR BALANCED THREE-PHASE ELECTRICAL EQUIPMENT

Harmonic Order	Limits
3rd, 5th, 7th	$I_3=I_5=I_7=0.02I_1$
Odd Triplen Harmonics (h=9,15,21,...,39)	$I_h=0.1I_1/h$
11th	$I_{11}=0.1I_1$
13th	$I_{13}=0.08I_1$
Odd Non Triplen Harmonics 17, 19	$I_{17}=I_{19}=0.04I_1$
Odd Non Triplen Harmonics 23, 25	$I_{23}=I_{25}=0.03I_1$
Odd Non Triplen Harmonics 29, 31,35,37	$I_h=0.3I_1/h$
Even Harmonics 2 and 4	$I_h=0.01I_1/h$
Even Harmonics >4 (h=6,8,10,...40)	$I_h=0.0025I_1$

Table 16-5 RTCA/DO-160G

As shown in Table III, the harmonic contents of the input current for a 12-pulse TRU is “richer” than that of a 24-pulse TRU. The 11th and 13th harmonics are very high (7.99% and 4.86% respectively). The maximum THD value is 9.63% at full load. The harmonics values for a 12-pulse TRU are below the limits set by the standards but in many applications it is required to reduce the 11th and 13th harmonics. This can be done by adding passive or active harmonics filters. This will affect the weight and volume of the TRU.

TABLE III
12-PULSE RECTIFIER INPUT CURRENT HARMONICS

Load%	THDI%	I_{11} (I_1%)	I_{13} (I_1%)	I_{23} (I_1%)	I_{25} (I_1%)
50%	7.43	6.17	3.86	1.01	0.77
60%	8.10	6.75	4.18	1.06	0.79
70%	8.61	7.18	4.41	1.17	0.87
80%	9.02	7.52	4.60	1.32	0.99
90%	9.36	7.78	4.74	1.48	1.11
100%	9.63	7.99	4.86	1.64	1.23

C. Comparison of power quality

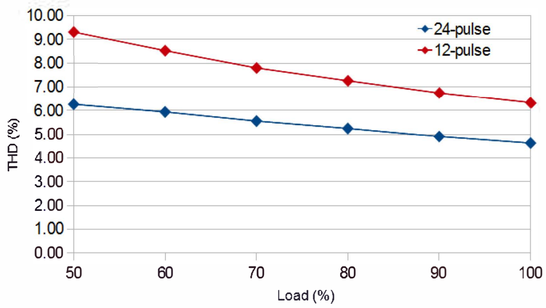
The main power quality parameters at the system input (voltage THD, current THD, power factor) are shown in Table IV for 12-pulse and 24-pulse TRU.

TABLE IV
COMPARISON OF POWER QUALITY PARAMETERS OF 12-PULSE AND 24-PULSE TRU

Load (%)	24-pulse			12-pulse		
	THDV (%)	THDI (%)	PF	THDV (%)	THDI (%)	PF
50%	6.26	2.43	0.9976	9.31	7.43	0.9885
60%	5.94	2.79	0.9973	8.53	8.10	0.9893
70%	5.56	3.07	0.9972	7.80	8.61	0.9900
80%	5.25	3.32	0.9971	7.26	9.02	0.9905
90%	4.91	3.50	0.9971	6.74	9.36	0.9911
100%	4.63	3.67	0.9971	6.33	9.63	0.9915

In both cases, we can remark that the voltage THD decreases while the current THD increases with increasing load. As expected, a 24-pulse TRU produces much less harmonics than an equivalent 12-pulse TRU having the same power rating. The improvement factor is more impressive with current THD than voltage THD. This factor is in the range of 2.62 to 3.06 for current THD while it is only from 1.367 to 1.487 for voltage THD. Regarding the input power factor, both TRU provide a value very near unity.

Fig. 11 shows the power quality parameters of 12-pulse and 24-pulse TRU in terms of the load.



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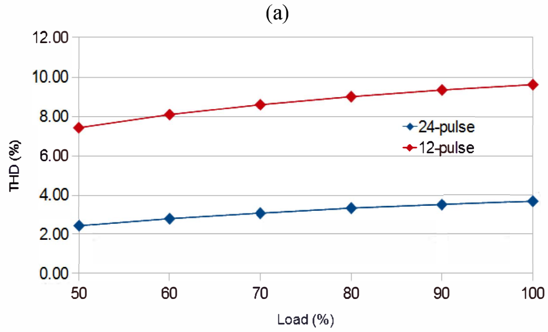

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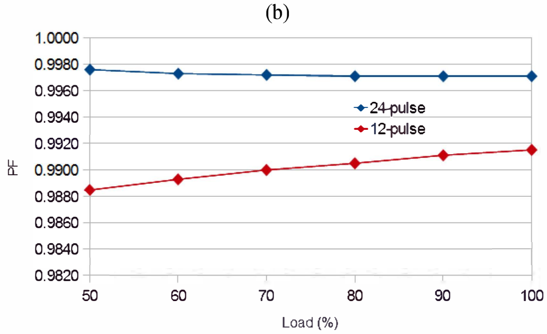

(c)

Fig. 11 Comparison of power quality for 12-pulse and 24-pulse TRU. (a) Input voltage THD. (b) Input current THD. (c) Input power factor.

VI. CONCLUSION

A 24-pulse Transformer Rectifier Unit has been modeled and studied. The simulation results obtained with a constant load have demonstrated a very good performance as compared with a 12-pulse TRU. The harmonic contents of both 12-pulse and 24-pulse systems meet the limits imposed by RTCA standards but the 12-pulse system produces a higher THD. To bring the THD of a 12-pulse TRU down to the same level as a 24-pulse TRU, it will be required to install active or passive filters. This will add weight and volume to the 12-pulse TRU.

Future work will include an evaluation of the weight and volume reduction obtained with a 24-pulse TRU and a study on the output voltage control in variable-frequency operation.

The 24-pulse TRU represents an interesting solution for More Electric Aircraft and its simple operation will facilitate its integration with other aircraft electric equipment.

VII. ACKNOWLEDGEMENT

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