Starter/Generator Employing Resonant-Converter-fed Induction Machine Part I: Analysis

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A new procedure to start a jet engine (JE) and to generate power by means of a single induction machine (IM) directly coupled to the turbine is presented. The JE is brought to an initial speed by the motoring operation of the IM. Later, the IM is taken into generating mode and the turbine is applied its excitation. The turbine catches up and starts to drive the induction generator (IG). The generated power is converted to a three-phase (3Ø), 400 Hz voltage-regulated bus via a double stage power conversion utilizing a 20 kHz parallel resonant high frequency (HF) ac link and pulse density modulated (PDM) converter technology. Independent of the engine speed, a constant amplitude and constant frequency 3Ø voltage-regulated ac bus is formed and maintained by the proper control of the power converters. Here the feasibility of operation of such a system has been demonstrated in software where the JE turbine is modeled and replaced by a dc machine. An introduction, background, operation priciples of the overall system, and the related software simulations are presented and discussed.

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I. INTRODUCTION

For aviation and space station applications it is very desirable and crucial to have smaller size, lighter weight, and lower cost system solutions. It is just for this reason that even though hydraulic systems have been the preferred choice over some years for certain applications, they seem to leave their places to their electromechanical counterparts as the more electric aircraft initiatives gain momentum [1–27]. Therefore, high frequency (HF) ac or pulsating dc links of various topologies have been proposed for such applications as a means of obtaining high power densities [Watts/kg] and for flexibility in accomplishing voltage level changes [26–41].

Aviation and space station application systems are members of a special class of drive system in which the converter/inverter is completely isolated from an infinite bus (stiff voltage source). Instead, these systems rely upon a small generator to supply power to the rest of the system. The research on the variable speed constant frequency (VSCF) technology with singly- and doubly-fed induction machines (IMs) has so far mainly focused on the wind power generation applications; whereas, with that of the switched reluctance machines (SRMs) VSCF technology has been directly studied as aircraft systems [7, 10–25]. The problem of controlling an aerospace system utilizing an induction generator (IG) is particularly important as it is a potential low cost solution to power such isolated systems.

In classical systems the starting up of a jet engine (JE) is achieved by means of various types of starter units such as electrical, fuel, penaumatic, cartridge, and penumatic-cartridge types. Most of these starters need pressurized air and ground base support units. A starter unit is used to aid the initial start and speeding up of the JE. A ground base support unit provides high pressure air to aid the process. The dependency of aircrafts on the ground base support units for their engine start-ups is a great disadvantage. A solution that will remove the dependency of aircrafts on ground base support units may be preferred at the expense of extra size, weight, and cost on the craft. This solution might be a battery and an associated motor starter.

The classical systems have two different machines for the starter and the power generator. The former is used to aid the start of the JE and the latter is used to generate the power required in the aircraft. Usually, a wound-field synchronous generator (SG) driven by a JE supplies the power required in the aircraft [43]. This power is in the form of a 3Ø, 400 Hz, 115 V bus. Either the stator terminals of the SG are used for the bus with the requirement of keeping the machine at synchronous speed to be able to generate power at constant frequency; such a system is called a constant speed drive (CSD) system and requires some mechanical gear and speed regulator systems which means considerable size, weight, and cost, or the generated power at the stator terminals is processed via double stage power conversion wherein through the first stage power is converted to an intermediary link and through the second from the intermediary link to the desired bus. This last system referred to as VSCF system is not limited to only synchronous machines (SMs) and may as well be applied to IMs and SRMs. Here the mechanical gear and speed regulator systems are eliminated.

A search and a comparative review of the literature available on VSCF technologies made by M. E. Elbuluk [7] presents two VSCF systems based on IM and SRM technologies. Based on this comparative review, the author recommends that the IM be fully investigated as a VSCF drive in aircraft system and the findings should then be compared with the counterpart SRM system. It is claimed that the VSCF systems provide better starter/generator schemes for aerospace applications and overcome certain limitations associated with various power types, reliability, maintenance, and higher operating speeds and temperatures.

Brushless doubly-fed machines have been investigated as VSCF generators for wind power generation where the output electrical power is maintained at 60 Hz and generation is obtained at low speeds [44]. These generators include systems based on IM and reluctance machine technologies.

The SRM is told to enjoy considerable interest for use as an integral starter/generator on future aircraft engines due to advantages in reliability, fault tolerance, high speed, high temperature, and high power density operation [7]. The ability to operate in high temperature environments and high speed operation is told to allow the possibility of direct drive and, hence, the elimination of gear-box and hydraulic system accessories on the aircraft.

In this paper, an IM directly driving/driven by a JE turbine during motoring/generating operation of IM, and the generation of 3Ø, 400 Hz, 115 V power via IM together with its 20 kHz parallel resonant HF ac link, associated converters and battery starter has been investigated. In previous studies, the IM is shown to be able to operate at high speeds as its counterpart SRM [37]. The IM together with the associated 20 kHz HF AC link and pulse density modulated (PDM) technology enjoys similar advantages as the SRM in terms of reliability, fault tolerance, high speed, high temperature, and high power density [28–41]. Besides the 20 kHz parallel resonant HF AC link provides quick isolation of faulty modules due to the zero crosssings of the link, less audible converter noise due to 40 kHz switching frequency, better harmonic spectrum at the input and output, high power density, and versatility in voltage level changes through the use of HF transformers connected to the link.

The investigations made so far with the SRM employ a traditional dc link to establish 3Ø, 400 Hz, 115 V power [13–25]. The dc link has not the advantages of versatility of voltage level changes and easy isolation of faulty modules as the 20 kHz ac link. If soft switching techniques are used for the inverter operating from the dc link, the dc link may have other high switching frequency advantages as well. But the size and the weight of the dc link should be compared with those of the ac link for the same level of system power.

When a constant frequency power supply is desired from an IG driven by a variable speed JE turbine, a double stage power conversion is the classical solution. With the first stage the power generated at the terminals of the IG is converted to an intermediary link and with the second from the intermediary link to a 3Ø, 400 Hz, 115 V voltage-regulated bus. In this way, it is possible to establish a constant frequency bus independent of the generator speed by controlling the converters. Of course, there would be a lower limit for the generator speed for a desired minimum power level of operation in the system. Thus, such a system might be classified as a VSCF power supply. On the other hand, the intermediary link utilized can serve multipurpose power supply needs and a fast system response solutions could be obtained depending on the switching frequency of the converters used.

In this paper, the feasibility of starting a JE, generating power, establishing and maintaining a 3Ø, 400 Hz, 115 V voltage-regulated bus with a single IM is investigated.

The feasibility of operation of the complete system has been demonstrated by means of software simulations in this paper, and via hardware prototype in another paper titled "Starter/Generator Employing Resonant-Converter-fed Induction Machine, Part II —Hardware Prototype".

II. BACKGROUND

Over about the past fifteeen years, research activities at The University of Wisconsin–Madison have focused on the development of an HF ac link power conversion system [28–41]. The HF ac link converter is a significant advance in the state of the art in power converter technology since the switching frequency of the power converter can be increased by an order of magnitude while, at the same time, reducing the switching losses. During the past fifteen years a complete double bridge ac link system has been constructed at the UW–Madison. The double bridge permits the electrical machine to operate at variable frequency with full bidirectional power flow in either rotational direction. The operation of a squirrel cage induction motor (IMO) operating

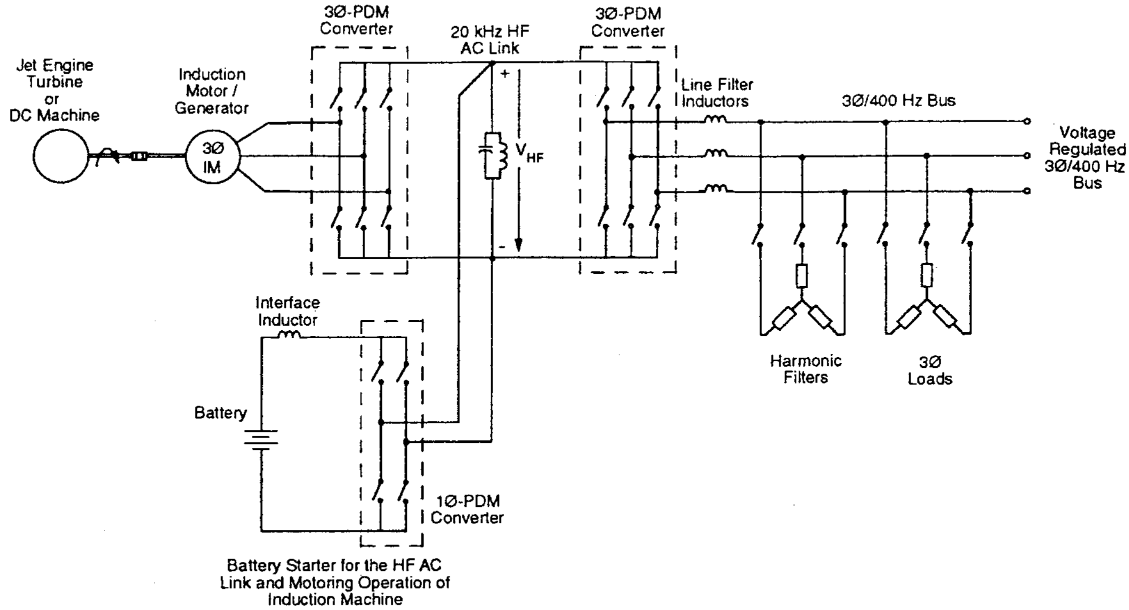

Fig. 1. Power circuit block diagram of battery started and IG maintained 3Ø/400 Hz bus utilizing 20 kHz parallel resonant HF ac link and PDM technology.

under closed-loop speed and torque control utilizing the field-oriented control (FOC) principle with both motoring and generating operation has been investigated and full reversibility of the direction of rotation of the IM has been demonstrated in hardware [30, 33–41].

Some of the recent studies have focused more on the average active power balance control of the overall system by a field oriented controlled (FOC) IG operating from 20 kHz HF ac link and an associated 3Ø PDM converter. Various types of feasibility of operations of the IG have been demonstrated both theoretically and experimentally [38–41]. The feasibility of an IG operating from a 20 kHz HF ac link and 3Ø PDM converter together with the management of a complete average active power balance of the overall system has been fully demonstrated on a flywheel load leveling system [38]. The concept has also been verified on a completely isolated 3Ø to 3Ø IMO/IG system both theoretically and experimentally [39–41]. The focus of attention though on these studies was not to start a JE by an IMO and supply the active power need of the system by the IG. In this work, the existing HF ac link at the UW–Madison is used to study the effectiveness of such operation of the IM and turbine pair.

III. OVERALL OPERATING PRINCIPLE OF THE SYSTEM

Fig. 1 shows the power circuit layout of the system under investigation. At first, the turbine is needed to be brought up to an initial speed before it catches up and begins driving the IG. This entire process requires that the IM should initially be started as a motor to bring the turbine to the desired speed. A battery along with the associated single-phase and three-phase full-bridge PDM converters are utilized to achieve this goal. Once the initial JE speed is achieved in this mode the IM is then taken into generating mode, the battery starter is disconnected and the active power need of the entire system is left to the IG alone. Later the 3Ø, 400 Hz, 115 V bus can then be established whenever desired.

Initially, a 20 kHz HF ac link is established via a battery starter and a single phase full bridge PDM converter. Once the HF ac link is established the IM is first excited and operated as a motor via the activation of a current-regulated 3Ø PDM converter. The control of the IM is by means of an indirect field-oriented controller with a simple bang-bang type current regulator. The IM can be operated in two different modes during motoring, one being the torque regulation mode and the other speed regulation mode. Through one of these modes of operations, the IM and the JE pair is brought from zero speed to the desired speed. In the torque regulation mode the speed is not regulated and must be observed to avoid over speedings. In the speed regulation mode torque component is commanded in a way to regulate the speed at its reference. During this mode, the battery side dc reference current is generated as shown in the control block diagram of Fig. 2 and regulated via associated single-phase PDM converter so as to maintain the average active power balance in the overall system. The dc reference current is generated proportional to the average active power required by the system and a minor proportional-integral (PI) peak link voltage regulator contributes to the

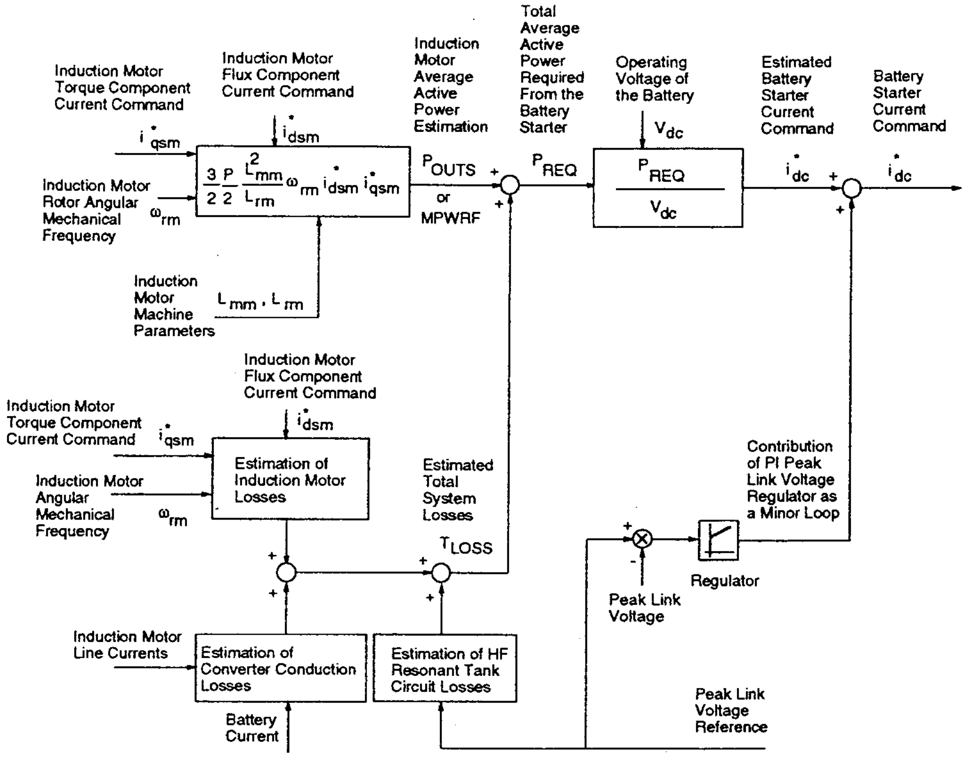

Fig. 2. Block diagram of average active power balance maintenance during operation of battery starter, motoring operation of IM, and estimation of battery starter current for given battery voltage and average active power need of system.

estimation. The jet turbine behavior in the actual system is simulated by a dc machine in software simulations.

After starting the IM as a motor and accelerating the rotor up to the desired reference speed, the IM is then switched to operate as a generator. The JE coupled to the shaft of the IM must begin driving the IM at this point. During the generating mode of operation, the generator must now operate in the torque regulation mode to control the power flow. This is not a simple task to accomplish since it implies that a very precise torque component current command estimation for the FOC IG is necessary to control the average power flow in the system. A control block diagram for this mode of operation is shown in Fig. 3.

During the torque regulation mode of operation of IG, the shaft speed of the generator could vary depending on the average active power demand from the IG. As the demand increases from the generator, the shaft speed of the generator tends to decrease. To be able to deliver the increasing power demand from the generator it is clear that the torque component current command of the generator must be increased as the speed decreases. There is, however, a lower limit on the generator speed both for a given average active power level and for the current ratings of the power switches used.

After the IG is set to maintain an average active power balance in the system, the 3Ø/400 Hz voltage-regulated bus for the aircraft power supply is established from the 20 kHz HF ac link through another dedicated 3Ø PDM converter as shown in the power circuit layout of Fig. 1. This bus is assumed to be 400 Hz at all times independent of the generator speed.

Initially, a detailed evaluation of control requirements has been considered and extensive computer simulations were undertaken to show the overall feasibility of the system. Since one of the main objectives is to focus on the maintenance of a regulated 3Ø/400 Hz bus with the least possible harmonic content, series line interface inductors and parallel filters have been installed to reduce the harmonic content of the waveforms on the bus. Hence, this study examines the harmonic distortion and its effect on the 400 Hz bus both before and after the utilization of appropriate filters.

IV. SOFTWARE SIMULATION OF THE SYSTEM

A computer program in ACSL (Advanced Continuous Simulation Language) has been developed to simulate the overall system whose power circuit diagram is shown in Fig. 1. In the first part of the simulations, a 10 Hp, 3Ø, 300 Hz, 6000 r/min Reuland Electric IM parameters [12–14] are used. This machine was considered to be coupled to a dc machine whose ratings are 10 Hp, 235 V, 37 A, 1750 r/min.

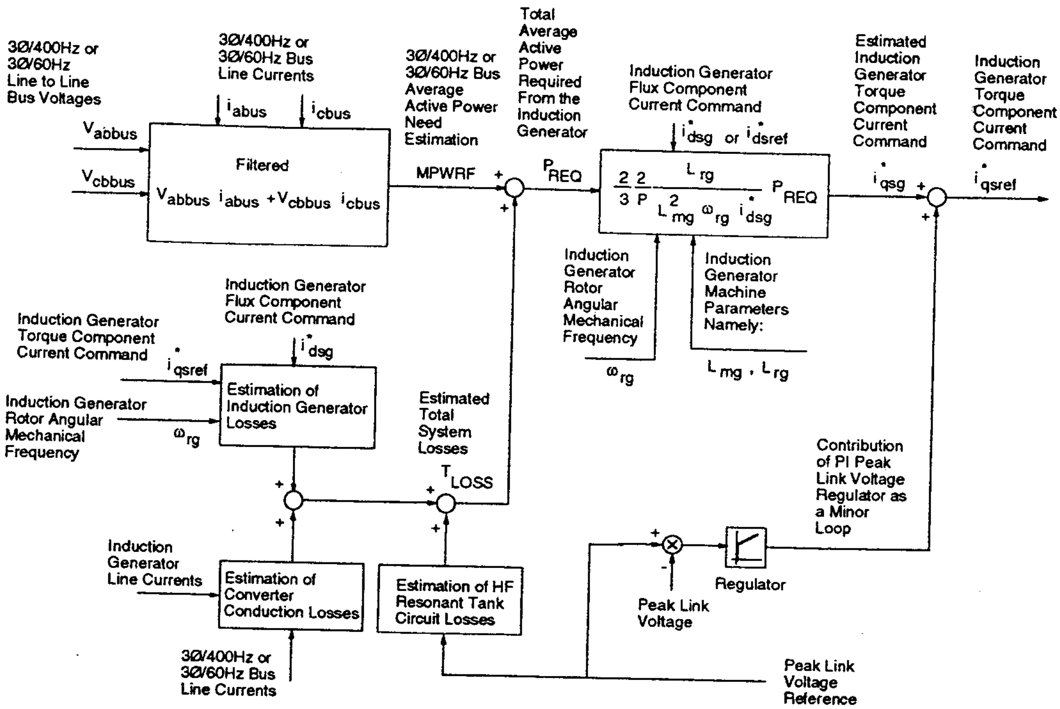

Fig. 3. Block diagram of average active power balance maintenance during generating mode of operation of IM, and estimation of torque component current command of generator for given average active power need of entire system.

In the software simulations, the IM is initially operated as a motor via an indirect field-oriented controller and brought to a speed of around 4000 r/min by means of a battery and 1Ø PDM converter by controlling the battery side dc current over the interface inductor. Later, the machine is taken into the generating mode and the power management of the system is left to the generator torque command. The battery is disconnected and the dc machine coupled to the IM is appropriately started to drive the IG.

In the later phase of the study, since a 30 Hp, 3Ø, 60 Hz, 230/460 V, 68.4/34.2 A, 3545 r/min Marathon Electric IM is considered for the full-scale hardware test the software simulations related to this machine are carried out. A 30 Hp, 250 V, 82 A, 1700–3600 r/min dc machine is selected for the JE turbine replacement.

Initially the 3Ø/400 Hz bus voltage is obtained using an area comparison PDM (ACPDM) technique. Without any filter all the waveforms are obtained with no problem. When the filters are introduced to have low total harmonic distortion (THD) bus waveforms serious control problems appeared. The problem is caused primarily by the resonant frequency of the filter inductor and the capacitor and the voltages existing at the resonant frequency due to the discrete nature of the control technique of synthesizing the voltage waveforms. Therefore, some type of damping has been the inevitable solution to this problem.

Initially, the effect of passive damping is studied. However, due to the undesired associated losses of the damper resistor, active damping is incorporated in the control scheme making the control of the system possible without using any passive damping resistors.

Once controllable filtered bus voltages are obtained, the effect of loading the bus is studied. Though the desired voltages at no load were readily obtained with some phase shifts the similar voltages were hardly obtained at loaded conditions due to increasing phase shifts and reducing magnitudes. This mismatch between the desired and obtained waveform is basically due to the voltage drop over the filter inductor and is very much dependent on the magnitude and phase of the current flowing through the inductor and the magnitude and the phase of the voltages on both sides of that inductor. Therefore, a feedback mechanism is required to compensate for the undesired magnitude and phase shift changes. Various definitions of the error term is studied in detail to obtain such a feedback mechanism and to determine the effectiveness of the related control strategies.

However, none of the voltage-regulation techniques using an ACPDM scheme is considered to be satisfactory at all operating conditions in the sense that there would remain considerable phase shift and magnitude difference between the filtered voltage and the desired reference. The related simulation results tested for different voltage-regulation techniques using an ACPDM technique are not incorporated here because the length of that study requires another paper.

Eventually, a control technique that would enable tolerable phase shift and magnitude is identified which appears to be suitable for all operating conditions. This control strategy turns out to be a current-regulation technique that would in turn also regulate the desired voltage at the filtered bus side. When the currents to the filter capacitors are regulated the voltages across the filter capacitors are automatically regulated. Tight regulation of the bus currents helps in decoupling the interactions between the inductor and the capacitor. Thus, the method prevents the undesirable effects of resonance and stability problems at the resonant frequency of the filter inductor and the capacitor requiring no damping for the output voltages.

A. Start-Up and Operation of the System

The power circuit layout of the entire system is shown in Fig. 1. In this system, the switches in the PDM converters are bidirectional in nature which are designed to allow bidirectional power flow through the converter. The switches are turned on and off at the zero crossings of the 20 kHz HF ac link voltage. Operation of the 1Ø phase converter is very simple and it is a boost type of converter. Detailed operation principles for the current-regulated 3Ø PDM converter is given in [37, 39]. Knowledge of the operating voltage of the battery and the average active power required by the system helps maintain the average active power balance of the entire system by controlling the average dc current over the inductor. A minor PI peak link voltage regulator loop helps regulate sudden variations of the peak.

The computer program for this study is developed in such a manner so as to simulate the 20 kHz HF ac link build-up as well as a soft start excitation of the IM. During the excitation of the machine only the flux component current command is applied. Once a sufficient flux level is established, a proper motor torque command is applied to the machine to drive it to the desired speed. Here the speed regulation mode of operation is preferred.

Fig. 4 shows software simulation outputs of such a start and consequent operation for the 10 HP, 3Ø, 300 Hz, 6000 r/min Reuland Electric IM case.

The first trace from the top in Fig. 4 shows the link voltage build-up and regulation.

The second trace from the top in Fig. 4 shows the dc current of the battery starter. Almost a constant average active power delivery from the battery to the system is observed after link voltage build-up and during the excitation of the IM at zero speed. The battery voltage is assumed to be 120 V dc in the simulations. When the IM is applied a torque command in the motoring and speed regulation mode, the average active power transferred from the battery to the system increases gradually as the speed of the machine increases. Once the desired speed is reached in motoring mode as seen in the figure at the beginning of 8th time division, the torque command is adjusted in a way to regulate the speed. The speed is regulated in this mode about one time divison and later around the beginning of 9th division the IM is taken into the generating mode. The single-phase PDM converter is disabled and the average active power balance task is left to the generator torque command and not to battery starter. The dc current of the battery drops suddenly to zero as it is disabled showing zero average power delivery from the battery to the system. Later the dc machine coupled to the generator is appropriately started to drive the generator. The starting of the dc machine would correspond to applying the necessary excitation to the JE turbine in the real world.

In the generating mode, the IM is initially operated to maintain the HF ac link via the associated 3Ø PDM converter.

The third trace from the top in Fig. 4 shows the soft started flux component current command reference of the machine. The upper limit of this current is set to the rated value which is 25.60 A peak.

The fourth trace from the top in Fig. 4 shows the d-axis rotor flux of the machine in the stationary reference frame.

The fifth trace from the top in Fig. 4 shows the torque component current command of the machine, and from this trace it is apparent that no torque command is applied until flux is established inside the machine. At time $t = 0.15$ s an upper limit torque command is applied and kept at that value until the desired speed is reached. Since the IMO is operated in speed regulation mode, when the desired reference speed is reached, the torque command is adjusted automatically by the controller to stay at the desired speed. Switching to the generating mode of operation is clear as the torque command was changed from its positive regulation value to a negative value that is sufficient to deliver the required average active power at that speed and excitation as seen from the fifth trace. This change corresponds approximately to the beginning of 9th time division.

The fourth trace from the bottom in Fig. 4 shows the speed of the machine. The machine is brought to a speed of approximately 4000 r/min in motoring mode and maintained at this speed in the generating mode via control of the directly coupled dc machine.

The third trace from the bottom in Fig. 4 shows the induced voltage across the armature winding of the dc machine. Since the dc machine is brought to a predetermined speed by an IMO before the dc machine begins driving the generator, it is desired that the armature voltage of the dc machine be as close as possible to the dc bus voltage to limit the inrush starting current of the dc machine when switching the operation from the dc generator to the dc motor. Near the desired speed the armature voltage is adjusted by adjusting the field of the dc machine so that the above-mentioned goal is achieved. This process of

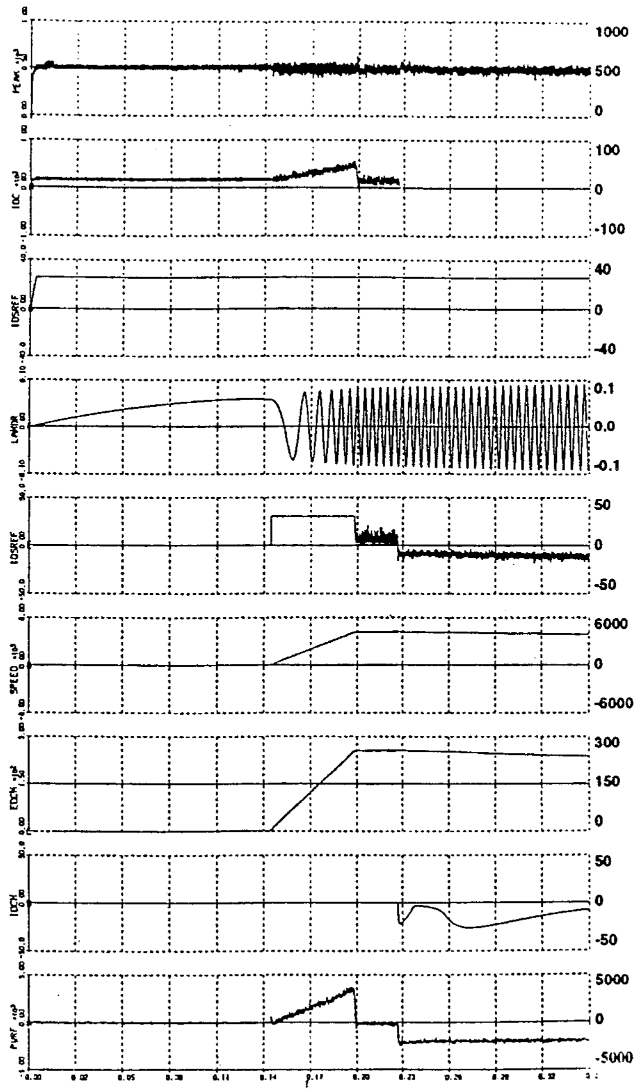

Fig. 4. Link voltage build-up, excitation and motoring operation of 10 Hp IM in speed regulation mode, switching to generating operation of IM, disconnection of battery starter, and generator as source of system. PEAK: Peak of HF link voltage in V. IDC: Battery starter current in A. IDSREF: Flux component current command of IM in A. LAMDR: Rotor d-axis flux of IM in stator reference frame in Vs. IQSREF: Torque component current command of IM in A. SPEED: Speed of coupled IM and dc machine in r/min. EDCM: Enduced voltage across armature winding of dc machine in V. IDCM: armature current of dc machine in A. PWRF: Measured and filtered active power at IM terminals in W. Time/div: 29.167 ms.

change of mode would correspond to applying the excitation of the JE in the real world.

The first trace from the bottom in Fig. 4 shows the filtered average active power as measured from the IM terminals. When the IM takes over the average active power balance in the system after the battery is disconnected, the machine continues to supply the power requirement of the system as long as it is driven by the dc machine.

When the machines are replaced with their 30 Hp counterparts the results of a similar computer run as in Fig. 4 is given in Fig. 5. As seen from the figure the excitation of the high power rated machine takes much longer. It should also be noted that the 30 Hp IM is a 60 Hz machine whereas its 10 Hp counterpart is a 300 Hz machine. Since the overall system is rated for about 10 kW operation any attempt to operate the system at higher power levels would cause instability due to the insufficient energy storage capacity of the resonant tank circuit. The simulations with 30 Hp machines are also carried out using the speed regulation technique during motoring mode of operation of the IM. Variables of the traces in Fig. 5 represents the same variables as in Fig. 4.

B. Establishing 3Ø/400 Hz Bus by a Dedicated 3Ø PDM Converter

After the IG is set to maintain an average active power balance in the entire system, the 3Ø/400 Hz voltage-regulated bus is established from the 20 kHz HF ac link through another dedicated 3Ø PDM converter.

1) *Utilization of Various Voltage-Regulation Techniques*: Due to the coupling between the

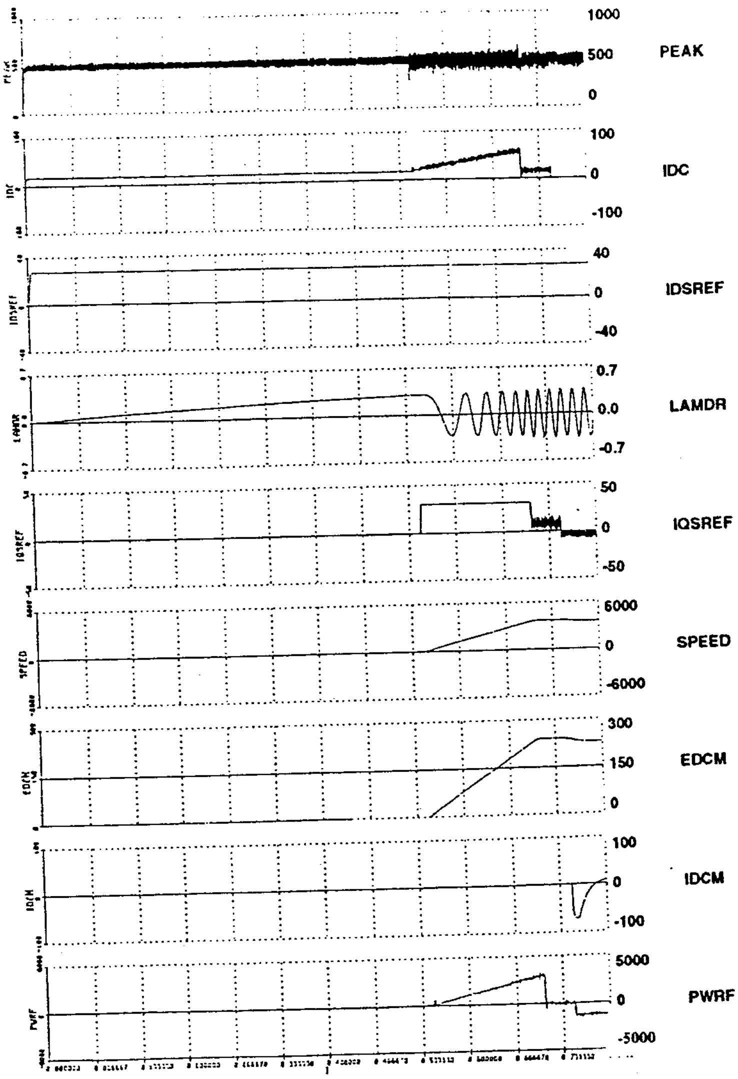

Fig. 5. Link voltage build-up, excitation and motoring operation of 30 Hp IM in speed regulation mode, switching to generating operation of IM, disconnection of battery starter, and generator as source of system. Same caption explanations as in Fig. 4. Time/div: 66.667 ms.

filter inductors and capacitors, solutions for stable operation of the bus are investigated to avoid potential resonances. Passive and active damping methods for the stabilization of the bus are studied. The effect of loading the actively damped bus is explored. None of the voltage-regulation techniques using an ACPDM scheme was considered to be satisfactory in the sense of reference and actual bus voltage matching. Some of these schemes are, however, satisfactory for certain operating conditions but not for all.

Eventually, a control technique with tolerable phase shift and magnitude is identified which is suitable for all operating conditions and the experimental phase of the studies is carried out by implementing only this type of control scheme. In this paper, all other control schemes are skipped and only the implemented one is explored.

2) *Utilization of Current Regulation Technique*: The control strategy that ultimately achieves a good matching between the reference and actual bus voltage for all operating conditions is a current-regulation technique where, by tightly regulating the currents to the filter capacitors, the filtered bus voltages across the filter capacitors are also regulated [42]. In addition, the tight regulation of the bus currents helps in decoupling the interactions between the filter inductors and the capacitors, thus preventing the undesirable effects of resonance and stability problems. It also eliminates the damping requirement for the output voltage caused by resonance and stability problems.

The filtering and loading of the 3Ø/400 Hz bus is depicted in Fig. 6. The phase-A bus current is defined as follows with the conventions in Fig. 6

$$i_{ABUS} = i_{AF} + i_{AL} \tag{1}$$

where i_{AF} = phase-A filter cap current, and i_{AL} = phase-A load current.

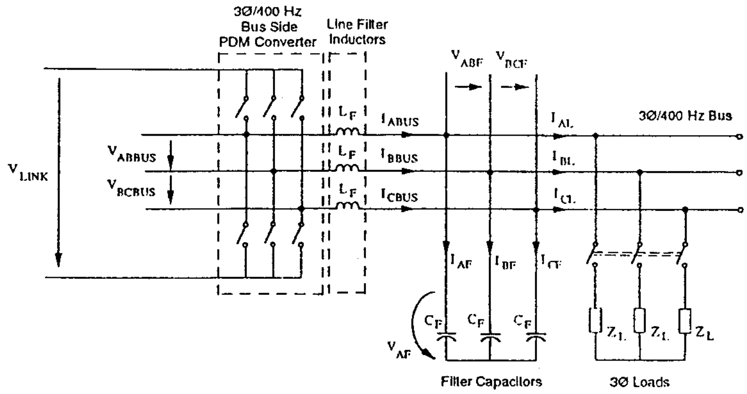

Fig. 6. Power circuit layout of filtering and loading 3Ø/400 Hz bus and depiction of voltage and current conventions.

Assuming the load currents are measured and known for all phases, convenient filter capacitor currents are generated to obtain the desired bus voltages and from the sum of the two the bus current references are generated.

Let us assume that the following phase-A bus voltage across the filter capacitor for phase-A of a 3Ø/400 Hz bus is desired to be established at all times independent of the load currents,

$$V_{\text{ABRF1}} = V_{\text{Inpkbref}} \sin(\omega_{\text{bref}} t + \varphi_1) = V^*_{\text{CAF}} \tag{2}$$

Since this reference voltage is at the same time the filter capacitor voltage for phase-A then the filter capacitor current for the phase-A should be as follows

$$i^*_{\text{AF}} = C_{\text{AF}} \frac{dV^*_{\text{CAF}}}{dt} \tag{3}$$

$$i^*_{\text{AF}} = \omega_{\text{bref}} C_{\text{AF}} V_{\text{Inpkbref}} \cos(\omega_{\text{bref}} t + \varphi_1) \tag{4}$$

Thus the 3Ø/400 Hz phase-A bus current reference should be commanded as follows:

$$i^*_{\text{ABUS}} = i^*_{\text{AF}} + i_{\text{ALmeas}} \tag{5}$$

The reference currents for the other two phases are derived simply by phase shifting the phase-A current reference by 120 deg. Once the reference currents for all phases are known and commanded accordingly, they are to be regulated via 3Ø/400 Hz bus side PDM converter controller by utilizing parallel resonant HF ac link and zero voltage switching scheme with a 40 kHz switching frequency.

After the incorporation of this new current regulation technique in the software program, the 3Ø/400 Hz bus was established by means of this new control method.

Fig. 7 shows the results of such simulation for a loaded case. The filter inductor and the capacitor values for this simulation are $L_F = 1.5$ mH and $C_F = 15$ μF, respectively. A partially inductive load is studied having a load resistance of $R_L = 10.0$ Ω and a load inductance of $L_L = 1.5$ mH per phase. The first three traces from the top in the figure shows the reference and actual bus currents for all phases. The reference currents are on the same trace with the actual currents for the same phase. The next three traces from the top show the unfiltered synthesized line to neutral bus voltages for all phases, respectively. The last three traces of the figure show the desired and the actual 3Ø/400 Hz bus voltages for all phases respectively. As seen from the figure there are little leading phase shifts in the actual voltage waveforms with respect to their references. The performance of the 3Ø/400 Hz bus looks promising.

Harmonic analysis of the waveforms obtained in the above simulation reveals the following information regarding their harmonic contents. The results are especially important since they relate information regarding the quality of the bus voltage before and after the filtering of the 3Ø/400 Hz bus. To gain space, only the phase-A variables are given; the results for the other phases are quite similar. The phase shift information should be considered with respect to the ideal pure sine waveform reference for that phase.

For the phase-A reference bus voltage:
V_{ABRF1}: 115 Vrms, 0° phase shift, 0% THD.
For the unfiltered synthesized phase-A bus voltage:
V_{ABUS}: 147 Vrms, 6.48° leading phase shift, 30.75% THD.
For the filtered phase-A bus voltage:
V_{AF}: 113.08 Vrms, 7.69° leading phase shift, 1.37% THD.
For the reference phase-A bus current:
i^*_{ABRF}: 4.335 Arms, 90° leading phase shift, 0% THD.
For the actual phase-A bus current:
i_{ABUS}: 4.368 Arms, 98° leading phase shift, 7.59% THD.

As seen from the last figure and the results obtained from the harmonic analysis, the small leading phase shifts in the output filtered bus voltages are caused by the slight leading phase shifts occurring in the actual regulated currents of the bus. These leading phase shifts in the actual currents with respect to their references are due to the bang-bang type of current regulation employed, the frequency of the output bus

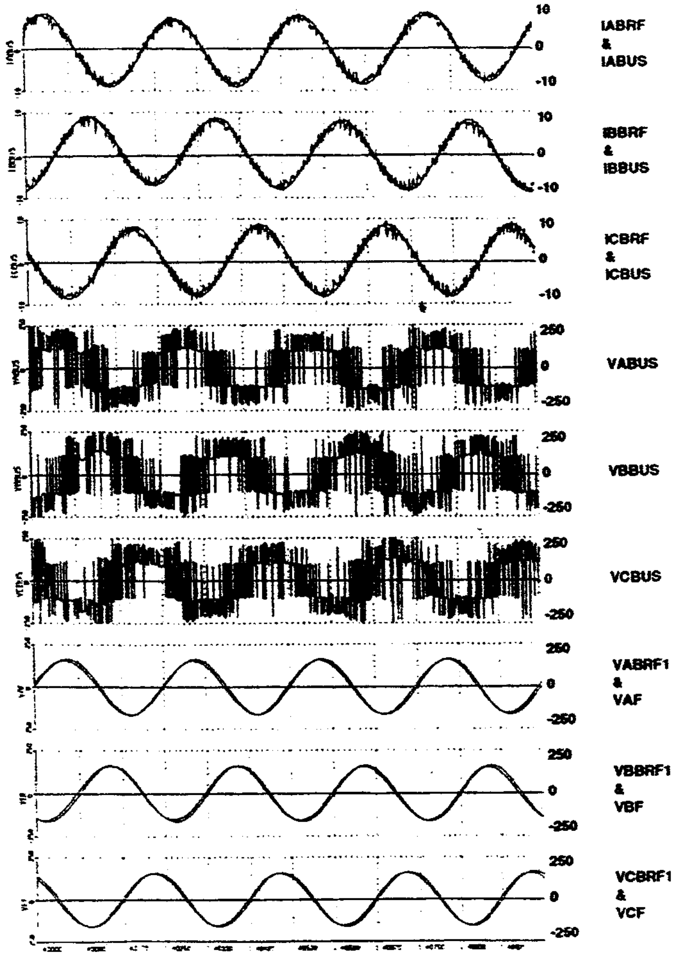

Fig. 7. Performance of the 3Ø/400 Hz bus with current-regulation technique at 10Ω and 1.5 mH inductive load and with filter (L_F = 1.5 mH and C_F = 15 μF). IABUS: Phase-A bus current in A. Similar for phase-B and C currents and their references. VABUS: Phase-A 3Ø/400 Hz unfiltered synthesized bus voltage in V. Similar for phase-B and C unfiltered synthesized bus voltage in V. VABRF1: Phase-A bus voltage reference in V. VAF: Phase-A filtered bus voltage in V. Similar for phase-B and C bus voltage references and filtered bus volatges. Time/div: 833.33 μs.

currents (400 Hz), and the switching frequency of the converter (40 kHz).

Despite the small leading phase shifts however, the overall performance of the filtered bus voltages and the currents are quite satisfactory.

V. CONCLUSIONS

Feasibility of starting a JE and generating power by means of a single IM mechanically coupled on a same shaft has been shown by means of computer simulations. Generated power at the terminals of IG has been converted to a 3Ø, 400 Hz, 115 V voltage-regulated bus via associated HF ac link and PDM converters. Various bus voltage regulation techniques are studied and among them a stiff current-regulation technique is found to be the most effective one, and only that is reported here. Independent of the engine speed, a constant amplitude and constant frequency and a very low THD ac bus waveforms is maintained by the proper control of the power converters.

REFERENCES

See References in Part II, pages 1327–1328.

Author photos and biographies are on page 1329.