AC/DC Power Systems with Applications for future Lunar/Mars base and Crew Exploration Vehicle

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Prepared by: Badrul H. Chowdhury, Ph.D.

Academic Rank: Professor

University & Department: University of Missouri-Rolla
Electrical & Computer Engineering Department
Rolla, MO 65409-0040

NASA/JSC

Directorate: Engineering

Division: Energy Systems Division

Branch: Power Systems Branch

JSC Colleague: Sabbir A. Hossain

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ABSTRACT

The Power Systems branch at JSC faces a number of complex issues as it readies itself for the President's initiative on future space exploration beyond low earth orbit. Some of these preliminary issues – those dealing with electric power generation and distribution on board Mars-bound vehicle and that on Lunar and Martian surface may be summarized as follows:

- Type of prime mover – Because solar power may not be readily available on parts of the Lunar/Mars surface and also during the long duration flight to Mars, the primary source of power will most likely be nuclear power (Uranium fuel rods) with a secondary source of fuel cell (Hydrogen supply).
- The electric power generation source – With nuclear power being the main prime mover, the electric power generation source will most likely be an ac generator at a yet to be determined frequency. Thus, a critical issue is whether the generator should generate at constant or variable frequency. This will decide what type of generator to use – whether it is a synchronous machine, an asynchronous induction machine or a switched reluctance machine.
- The type of power distribution system – the distribution frequency, number of wires (3-wire, 4-wire or higher), and ac/dc hybridization.
- Building redundancy and fault tolerance in the generation and distribution sub-systems so that the system is safe; provides 100% availability to critical loads; continues to operate even with faulted sub-systems; and requires minimal maintenance.

This report describes results of a summer faculty fellowship spent in the Power Systems Branch with the specific aim of investigating some of the lessons learned in electric power generation and usage from the terrestrial power systems industry, the aerospace industry as well as NASA's on-going missions so as to recommend novel surface and vehicle-based power systems architectures in support of future space exploration initiatives. A hybrid ac/dc architecture with source side and load side redundancies and including emergency generators on both ac and dc sides is proposed. The generation frequency is 400 Hz mostly because of the technology maturity at this frequency in the aerospace industry. Power will be distributed to several ac load distribution buses through solid state variable speed, constant frequency converters on the ac side. A segmented dc ring bus supplied from ac/dc converters and with the capability of connecting/disconnecting the segments will supply power to multiple dc load distribution buses. The system will have the capability of reverse flow from dc to ac side in the case of an extreme emergency on the main ac generation side.

INTRODUCTION

On January 14, 2004, US President Bush announced a new vision for NASA [1]:

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond;
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.

The vision has two specific initiatives:

1. Lunar Exploration

- Begin robotic missions to the Moon by 2008, followed by a period of evaluating lunar resources and technologies for exploration
- Begin human expeditions to the Moon in the 2015 – 2020 timeframe

2. Mars Exploration

- Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration.
- Timing of human missions to Mars will be based on available budgetary resources, experience and knowledge gained from lunar exploration, discoveries by robotic spacecraft at Mars and other solar system locations, and development of required technologies and know-how.

Both initiatives will require NASA to develop and demonstrate power generation, propulsion, life support, and other key capabilities required to support more distant, more capable, and longer duration human and robotic exploration than ever done before. This report describes the requirements for power generation and distribution for human habitat on lunar/Martian surface and provides a preliminary system-level design. Preliminary discussions are also provided for a power system for the proposed VASIMR engine.

Power Systems for lunar/mars habitation

Fig. 1 shows the essential ingredients of a power system for future space applications.

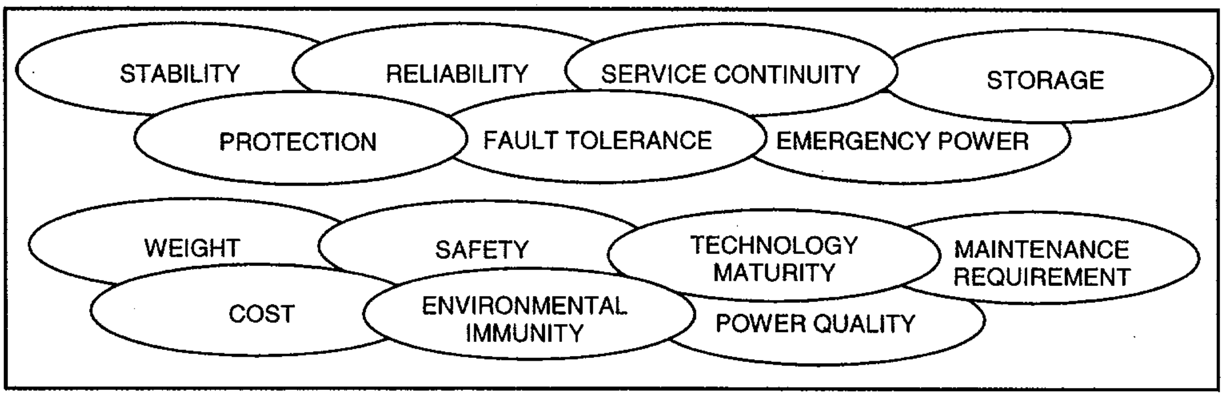

Fig. 1. Considerations for power systems for future space applications.

Undoubtedly, these characteristics are much more stringent than those expected of terrestrial power systems. The technological challenges in power systems for future space exploration are formidable and will require a careful study of what technology is available today and what needs to be developed before the vision can become a reality.

A.2 Power System for the VASIMR rocket engine

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) engine - a plasma-based propulsion system - will provide a new method of propulsion that can reduce interplanetary flight time [2]. High frequency radio waves are used to create electric fields to ionize gas (hydrogen, helium, or deuterium) particles creating plasma in a magnetic field. Low frequency radio waves are then used to add rotational energy to the ions in the cyclotron. A decrease in the magnetic field converts rotational energy of the ions into parallel energy. The ionized gas is then exhausted, thus providing thrust. The mass flow rate of the gas into the ionization chamber is controllable with a throttle, thereby changing the specific impulse of the engine. The VASIMR Engine has the capability to reduce travel time, making manned missions to Mars a distinct possibility in the future.

The engine can produce high power density with thrust velocities reaching 30,000 to 300,000 m/s. The engine is capable of varying the amount of thrust generated, allowing it to increase or decrease its acceleration. Electrical power sources for the VASIMR engine will most likely be a nuclear prime mover source running either a synchronous or an asynchronous machine with a rating of 5 to 10 megawatts of power.

AC AND DC SYSTEMS

Terrestrial power systems in the US and abroad consist of mostly ac generation with ac transmission serving mostly ac loads. More than 99% of the ac generation is accomplished by three phase ac synchronous generators. A very small percentage of generation in terrestrial power systems is done by solar photovoltaic systems (producing dc), and wind power generations systems (asynchronous generators generating variable frequency ac). Fig. 2 shows an example of a balanced 3-phase system represented by a one-line diagram. Generally, such a system is a 4-wire system.

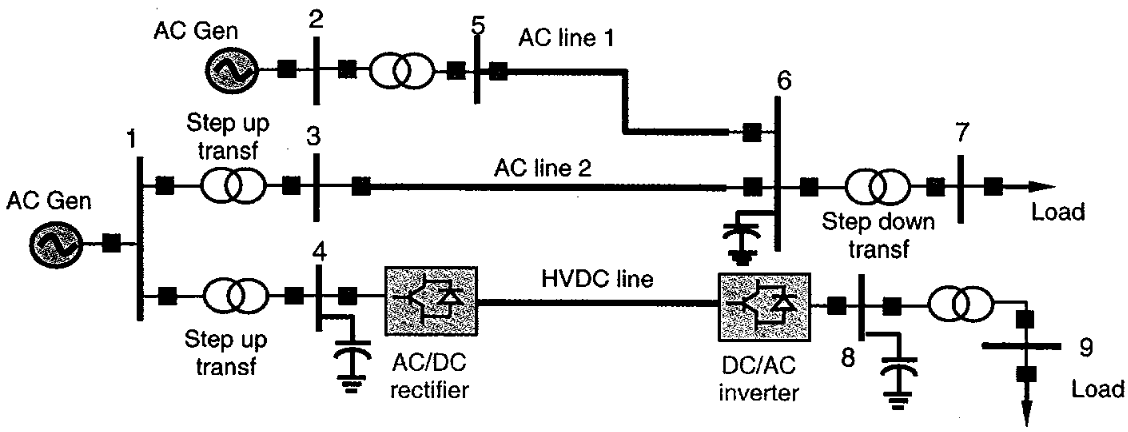

Fig. 2. A balanced 3-phase system represented by a one-line diagram showing 2 generators, 9 buses (nodes), 5 transformers, 2 ac lines, 1 HVDC line, 3 shunt capacitors, and 2 loads.

Three specific advantages of ac systems over dc systems should be noted. These are:

1. Synchronous generators will generate power in pure ac form. No filtering is required.
2. The synchronous generator source may be generally considered an infinite source, meaning that voltage (or frequency) will not drop excessively at the source with higher load currents. Dc sources, such as a battery, exhibits a drop in voltage as it discharges.

3. Voltage conversion is relatively easy by means of transformers with no additional filtering requirements.

Even a dc machine internally generates an ac voltage form which is mechanically converted to ac by means of commutators. Although the commutated voltage waveshape can be made to resemble a clean dc wave, the commutator requires periodic maintenance, has been known to fail more frequently than the rest of the dc machine, and is responsible for the higher cost of the dc machine. The concept of brushless dc machines was developed primarily to circumvent the disadvantages of the commutator. A brushless dc machine is simply a synchronous machine with a rectifier at the terminals to produce dc voltage. Hence, this machine suffers from the same disadvantages as an asynchronous machine with a power electronic interface. Incidentally, brushless dc motors are extensively used in hard disk drives and many industrial applications, and their market share is growing significantly in automotive, appliance and industrial applications.

Thus the technology exists to generate dc power. However, since voltages in dc systems cannot be transformed as easily as in ac systems, one has to resort to power electronics-based power conversion to bring about voltage step-up or step-down. Therefore, power electronic converters consisting of static semiconductor switches that are switched at fairly high frequencies, are used for this purpose. Unfortunately, converters create undesirable harmonics and electromagnetic interference (EMI) thus requiring use of filters. Additionally, the sensitive electronics inside the converter boxes have to be protected from faults.

Efficiency of AC systems

Transformers are about 90 – 95% efficient. Converters tend to be the same, perhaps a little less because of switching losses. DC systems are inherently less lossy because of the absence of reactive power. However, the resistive losses in dc lines are comparable to those in an ac line. For an understanding of how reactive power in ac systems leads to higher current magnitude, see Chapter 8 of IEEE Std 141-1993 - IEEE Red Book [3].

Line length and size of AC systems

Unlike a three phase ac system which requires at least three wires to carry current, dc power can be transmitted with only two wires (sometimes one). For a given ac voltage transmitted on a conductor, an HVDC system can carry 1.4 times that voltage on the same wire since an ac system's effective voltage is only 70.7% of the peak voltage. Therefore less insulation is needed for the wires.

Control and Stability of AC systems

DC power is inherently easier to control and re-route than ac power because of the absence of reactive power. In an ac system, active power can flow in one direction and reactive power in the other! Also, in the absence of line reactance in dc systems, power transfer is only limited by the thermal capacity of the line and not the steady state stability limit as is the case in ac lines.

Fault currents in AC systems

With high voltage DC, special attention should be given to fault propagation. Arc and corona suppression is of concern with higher voltage DC, especially at altitudes above 20,000 feet. Another consideration is the magnitude of the fault current with high voltage DC. Physical separation of high voltage and controls must be maintained. An advantage of DC is that simple make-before-break power transfers can be implemented to provide interrupt-free power transfers.

C. AC POWER CURCUITS

AC Power Generation

Typical options for bulk power generation, at the central station level based on fuel sources, include mostly coal-fired, natural gas-fired, water-powered, nuclear-powered, and petroleum-fired generations [4]. The common characteristics of terrestrial power generation are:

- A number of identical individual power generation units (hydro plants have larger units) make up a power plant usually in the hundreds of megawatts range.
- Many large power plants are located close to the fuel source. For example, the Jim Bridger power plant is located at Rock Springs, WY near a coal mine. The Grand Coulee power plant is located at the Grand Coulee dam on the upper Columbia River. Locating power plants close to the fuel source is still considered to be economically advantageous than transporting the fuel to a remote plant.
- More than 99% of bulk electric power is generated by 3-phase synchronous generators operating at 60 Hz frequency (50 Hz in most European and Asian countries).
- Maximum unit size in use today is 1300 MW.
- Most turbo-generator units (non-hydro) in the US have axial shafts and rotate at 1800 or 3600 rpm, while hydro-generators have vertical shafts and rotate at or below 1800 rpm.
- Power is generated at lower voltages. Typical generation voltage ratings (at the low side of the unit step up transformers) are: 240V, 480V, 600V, 2.4 kV, 4.16 kV, 6.9 kV, 13.8 kV [5]. Higher voltages (up to 23 kV) are possible with larger capacity generators. The limiting factor for high voltages are winding insulation and cooling requirements.
- The generated voltage is stepped up to much higher transmission voltages (138 kV to 765 kV. 1100 kV is also found in a few instances) by transformers in the switchyard.
- The generators are equipped with an exciter/AVR (for voltage and power factor control at the output) and a speed governor (for frequency control at the output of the gen).

AC Power Transmission

Because high voltage AC transmission lines have associated electric and magnetic fields, the mathematical model of a line includes both inductance and capacitance as shown in Fig. 3. Often, for short lines – lines shorter than 150 miles, the shunt capacitance of the line may be neglected. Additionally, line reactances for high voltage lines are much larger than line resistances. The electrical models of a synchronous generator and a transformer also include inductive reactances. The presence of these inductive reactances in an ac circuit can cause excessive voltage drops in the line unless somehow compensated for. Sometimes, mostly during high demands conditions, this situation leads to the voltage magnitude at the receiving end (load end) being much smaller than at the sending end.

Fig. 3a. One-line diagram of a transmission line

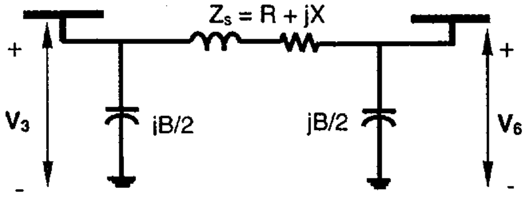

Fig. 3b. Electrical model of a transmission line

Mathematically, the voltage change between the sending and receiving ends of a line may be given by the following equation:

$$\Delta V = RI\cos\theta \pm XI\sin\theta \quad (1)$$

where R = line resistance
X = line reactance
I = line current magnitude
θ = power factor angle

In (1), "plus" is used when the power factor is lagging and "minus" is used when the power factor is leading. Also, the $XI\sin\theta$ term is much larger than the $RI\cos\theta$ term and therefore, the reactive power flow has a much larger impact on the voltage change than the resistive power flow. In summary, ΔV is positive when the power factor is lagging and negative when the power factor is leading.

Three methods may be used to increase the receiving end voltage as listed below:

1. Increase voltage at the sending end. If using a synchronous generator, this simply amounts to increasing the set (reference) point of the voltage regulator associated with the excitation system which will then increase field excitation, thereby raising the reactive power output of the machine.
2. Compensate for the series reactance in the line by series capacitors.
3. Apply shunt compensation at the load. Use *CVT, Statcom* [6], etc.

Method 1 does not improve voltage regulation; it only helps to increase the voltage magnitude at the receiving end. In fact, the reactive power flow in the line increases in this method. Method 2 decreases the line reactance and is therefore capable of improving the load voltage as well as improving voltage regulation. However, there are resonance issues associated with this technique in addition to being a more expensive proposition. Method 3 is the most effective solution strategy from the perspectives of economy, voltage regulation and voltage stability. This method works well because it is able to decrease the reactive power flow in the line which also helps improve the power factor.

Stability of AC Circuits

Although the reactive power needs of the receiving end of an ac power system may be satisfied by means of reactive power generation at the source end, the reactive power flow increases in the transmission links leading to higher losses, which in turn leads to higher power generation at the source. In this situation, the maximum loadability point may be reached as shown in Fig. 4a. One may also observe the time evolution of the receiving end bus voltage which may continue to decrease even though shunt compensation is applied at the load, as shown in Fig. 4b. This condition is symptomatic of *voltage instability* and unless corrective actions are taken, the receiving end voltage may *collapse.*

Transmission Voltage And Frequency

Effect of voltage levels

Higher voltage levels are an advantage for power transmission because of lower transmission losses. However, higher voltages create higher electric field strength and are therefore conducive for the phenomenon of corona to occur. Thus line diameters have to be increased to compensate for this possibility, making lines heavier. Higher voltages also produce higher stress levels for insulation.

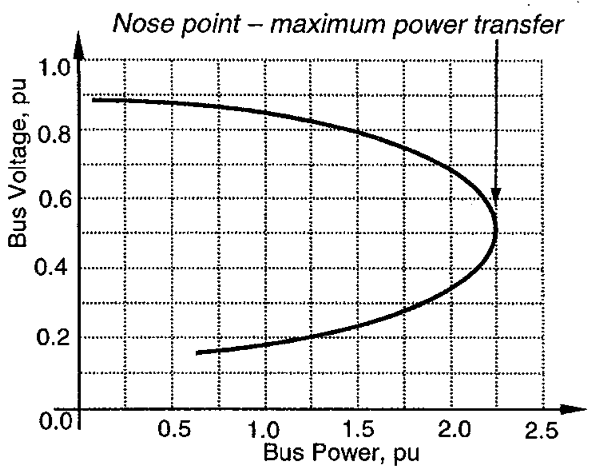

Fig. 4a. P-V curve showing bus voltage variation with real power

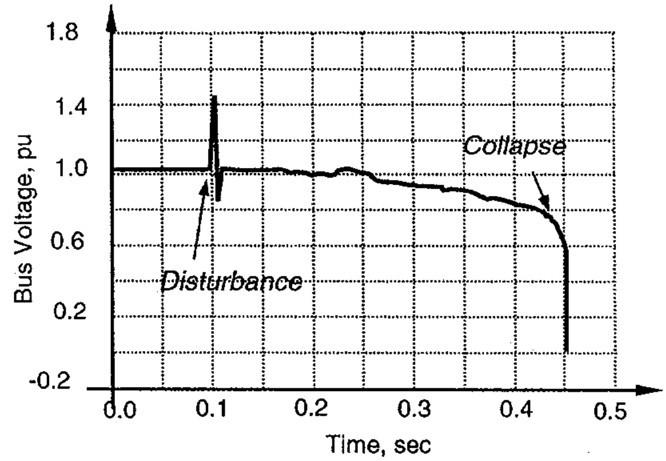

Fig. 4b. Voltage plotted as a function of time following a disturbance

Effect of frequency

The size and weight of transformers and energy storage elements decrease as the ac transmission frequency increases because of better utilization of the iron core. However, core losses in the magnetics (only 2-3% in 60 Hz transformers) and voltage regulation increase due to higher leakage reactance of transformers and line reactances of lines.

In dc transmission lines, the current is uniformly distributed through the conductor's cross section. However, in ac transmission lines, increasing frequency tends to crowd the current toward the outer perimeter of the conductor – *skin effect.* Since the line resistance is inversely proportional to the effective area of the conductor, it increases as frequency increases (proportional to square root of frequency) leading to higher losses. The resistive loss can be minimized and conductivity increased by plating the line with silver. Since silver is a better conductor than copper, most of the current will flow through the silver layer.

Higher frequency also has an impact on the short circuit capacities (SCC). It tends to lower the SCC as it is inversely proportional to the series reactance. Weaker systems have to be heavily capacitor compensated so as to maintain the required voltage at the load point. Additionally, at high frequencies, the X/R ratio of the wire tends to be large. This leads to lower amounts of damping during faults.

For buried cables, the shunt conductance is larger at higher frequencies leading to higher leakage currents. Thus ac frequency is an important parameter to consider for trade studies.

Building Fault Tolerance into Power Delivery

The rationale for building fault tolerance is to reduce the impact of faults by creating redundancies and providing looped sources with automatic transfer switches [7-11]. Fig. 5 shows a block diagram view of the various levels of redundancies in a simple power system. The configuration shown in Fig. 5(e) is preferred for the lunar/Mars habitat.

Voltage Transients – Switching Surges

Generally, any switching operation - fault initiation, interruption, operation of automatic transfer switches, etc. in a power system may be followed by a transient phenomenon in which transient overvoltages (TOV) can occur [12]. The sudden change in system condition can generate damped oscillations with frequencies higher than the fundamental and determined by the resonant frequencies of the network. A capacitor switching voltage transient can be seen in Fig. 6. The magnitude of the switching overvoltages depends on:

- the type of circuit (RLC)
- the kind of switching operation (closing, opening, restriking)
- the type of loads
- the type of switching device or fuse

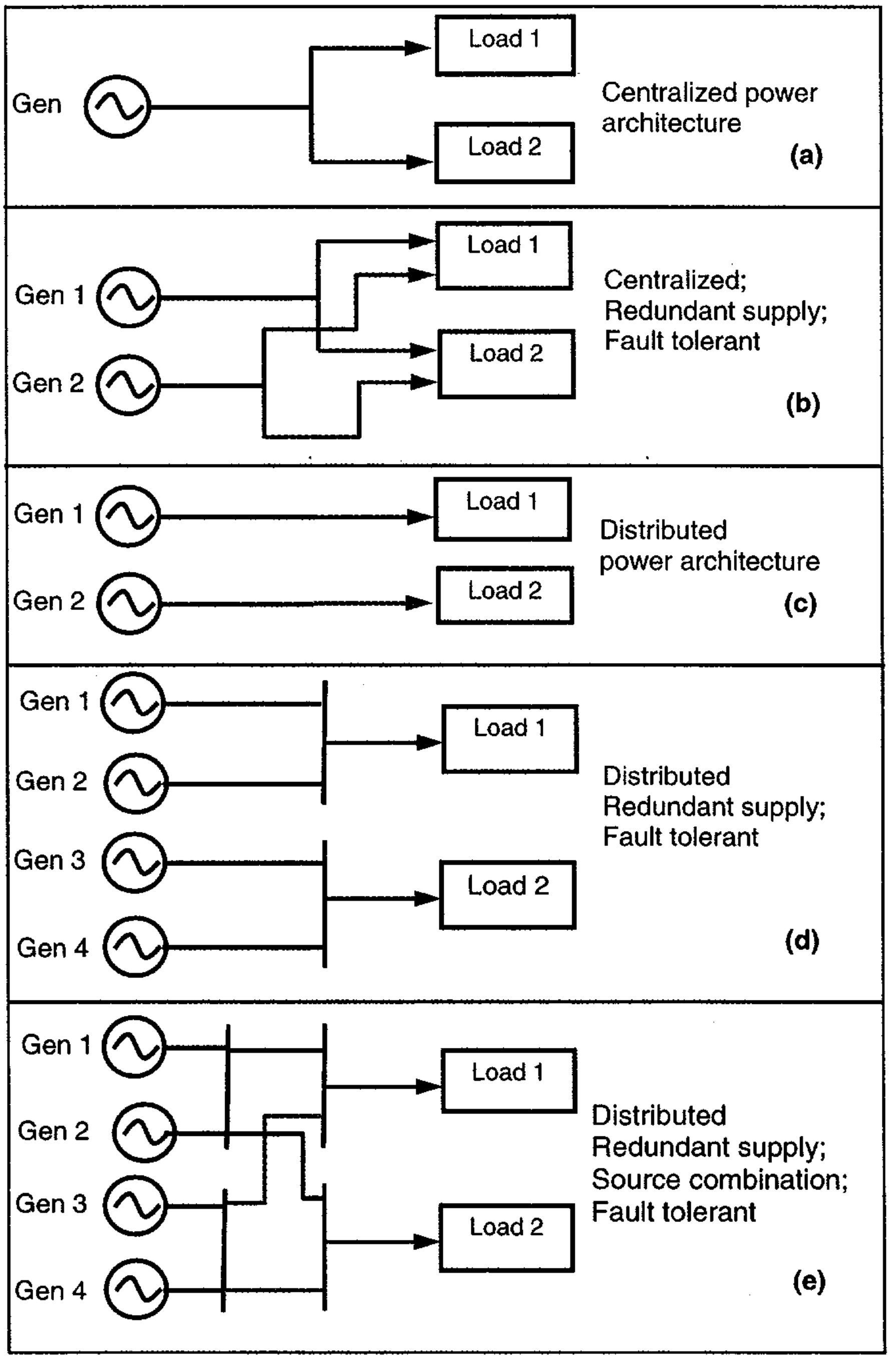

Fig. 5. Levels of redundancies provided by centralized and distributed power systems.

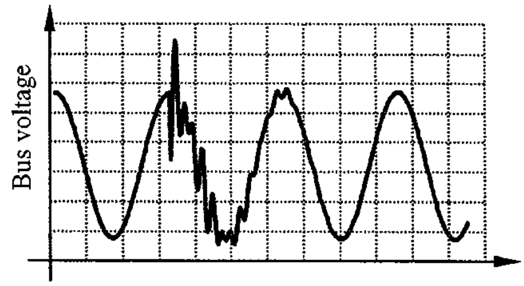

Fig. 6. Voltage transients due to capacitor switching.

The maximum transient voltage under any one or more of the following conditions:

- Instant at which the initiating event occurs – maximum TOV if it happens at the system voltage peak. (Note: the offset power-frequency current is greatest breaker closing at voltage zero).
- If a resonance condition exists in the system. System capacitor and inductance in resonance with load side capacitor.
- Whether ferroresonance condition exists
- Whether a capacitor restrikes.

TOV due to faults between line and ground

Depending on the configuration of the grounding, the fault current flows into one or more ground electrodes and generates ac overvoltages in the low-voltage system (load side) by ground coupling. The main parameter that influence the value and the duration of the TOV is the type of system grounding of the medium-voltage network

- Isolated (long time)
- Resonant-grounded (long time)
- Grounded through an impedance (longer time for high impedance and shorter for low-impedance grounded types)
- Solidly grounded (shorter time)

TOV due to a short circuit between line and neutral conductors

After the transient situation, the magnitude of the short-circuit current is limited only by the impedances of the supply and building wiring. The currents involved can be very high, ranging between one hundred and tens of thousands of amperes. A protective device operates to clear the fault. During this period of a few milliseconds to a few hundred milliseconds (but in all cases less than 5 s), a TOV can occur in the unfaulted lines of the affected power circuit.

THREE PHASE AC SYSTEMS

The advantages of three-phase AC systems are:

- Most AC generators are three-phase.
- Some power conditioning and electronic load equipment are operable only from a 3-phase power source.
- 3-phase systems may generally support larger loads with greater efficiency.
- The source impedance of three-phase systems is generally lower than 1-phase systems, which is important to minimize voltage waveform distortion due to nonlinear load currents.

Although three-phase voltage may be developed by different means, it is considered best practice to actually generate true three-phase power rather than convert single phase power (or dc power) to three-phase power. The methods to derive 3-phase power from 1-phase power ranges from using power electronics (1-ϕ ac to dc to 3-ϕ ac) to using single-phase motors turning a 3-phase generators, none of these is recommended by IEEE Std. 1100 [13].

Three Phase 3 or 4 Wire Systems

Three phase systems can be either 3-wire or 4-wire systems (Figs. 7a through 7d).

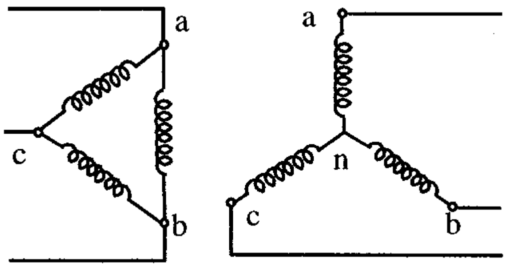

Fig. 7a. A 3-phase 3-wire ungrounded system.

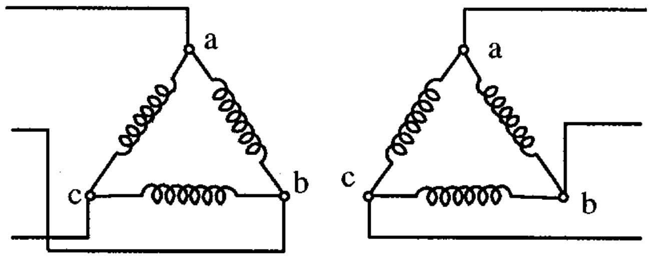

Fig. 7b. A 3-phase 3-wire ungrounded system

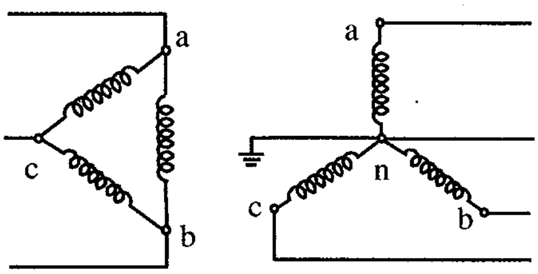

Fig. 7c. A 3-phase 4-wire system with neutral solidly grounded.

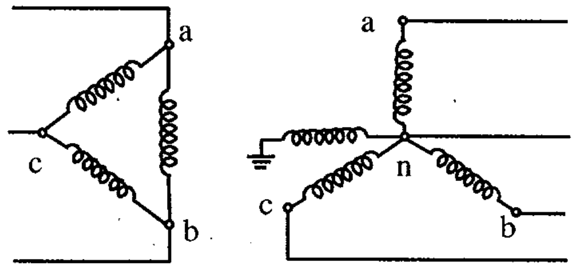

Fig. 7d. A 3-phase 4-wire system with neutral grounded through reactor.

Voltage Conversion (Transformer Connections)

Three phase transformers may be connected in any one of five configurations:

a. Y-Y (neutral grounded, ungrounded)
b. Y-Δ, Δ-Y (neutral grounded, ungrounded)
c. Δ-Δ (mid point grounded or ungrounded)
d. Special design (open delta)

Power systems do not generally use Δ-Δ configuration in low voltage systems because of its inability to provide lighting loads from a line to neutral voltage source. However, there are some advantages in using this configuration. If the Δ-Δ transformer is made of a bank of three single phase transformers, the system would continue to operate from just two transformers in an open delta configuration. However, the power capability is reduced and there is some amount of unbalance in the voltages.

Grounding

System grounding implies connecting the neutral point of a circuit element (rotating machine, transformer, etc.) on the system to ground either solidly or through a current limiting resistor or reactor. An ungrounded system has no intentional connection between a conductor and ground. However, a capacitive coupling may exist between conductors and the adjacent grounded surfaces. Thus, an "ungrounded system" may be considered as a "capacitively grounded system" as shown in Fig. 8. Based on grounding, power systems may be classified as:

- o Solidly grounded
- o High resistance – used in low voltage (<600 V) systems
- o Low resistance
- o Ungrounded

Advantages of grounding

- Grounding offers a reference potential of zero volts.
- Allows ground faults to be detected thus allowing fast isolation of faulted part.
- The phase conductors are stressed at only line-to-neutral voltages above ground.
- Lower voltages in unfaulted phases during short circuit faults. See simulations.

The disadvantages include possibility of higher short circuit currents during short circuit faults.

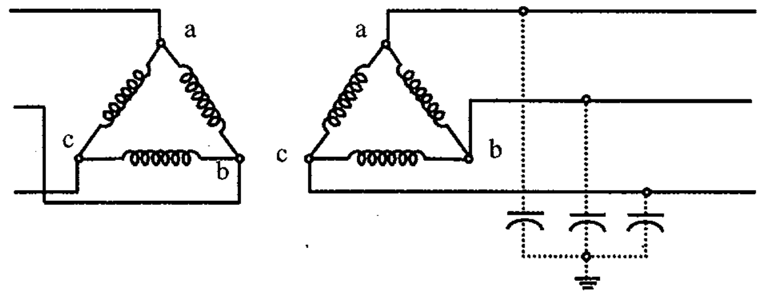

Fig. 8. A 3-phase 3-wire system with capacitive coupling to ground.

Ungrounded Systems

IEEE Standard 142-1991 [14] states that systems rated at 1000 V or less are suitable for ungrounded operation. The advantage of ungrounded systems is that no fault current will flow during a ground fault as there is no return path to the source. Therefore, the circuit will continue to operate safely after the first ground fault unless a second ground fault occurs. Such a situation is shown Case 3 of Appendix A.

A disadvantage of ungrounded systems is that in case of a ground fault, the other phase voltage will be subjected to full line-line voltages. Besides, the fault (or even normal switching activity) may result in high transient overvoltages (TOV) due to distributed capacitance of the line. Such high TOV may damage insulation or other pieces of sensitive equipment.

Another problem with ungrounded systems is the difficulty in locating or detecting faults. For these reasons, it may be advisable to apply high impedance grounding. Of course, in high impedance grounding, one must ensure that the impedance is low enough that the ground fault current is greater that the system's total capacitance-to-ground charging current. Otherwise, TOV may occur. IEEE Std. 141-1993 [3] states that high impedance grounding provides the same advantage as an ungrounded system, but additionally, limits the TOV.

400-Hz Power Generation

Some of US Navy's newest ships use 400 Hz, 3-phase nuclear power generation [15]. The current state-of-the-art in aerospace power is 400 Hz, 115 V (line-neutral), at either variable frequency or constant frequency [16-34]. Current aircraft electric power generation technology uses both the constant speed drive (CSD) [21-22] and the variable speed constant frequency

(VSCF) [23-27] technology. The CSD is an engine mounted generator system complete with an electrical generator and a variable displacement pump that constantly adjusts the output shaft rotation to maintain 24,000 RPM regardless of the throttle setting of the engine. The VSCF system is becoming the technology of choice lately mainly because of the advantages that power electronics provides from the perspective of weight and reliability. Fig. 9 shows a block diagram of such a system.

Electric power consumption on aircrafts will increase with the more electric aircraft and fly by wire paradigms now sweeping the industry [21, 22, 26]. Some of the concepts described here may be applied to future space exploration applications. However, the latter systems have to demonstrate a higher level of fault tolerance and reliability because of the long duration, relatively maintenance-free operational requirement in harsh environments.

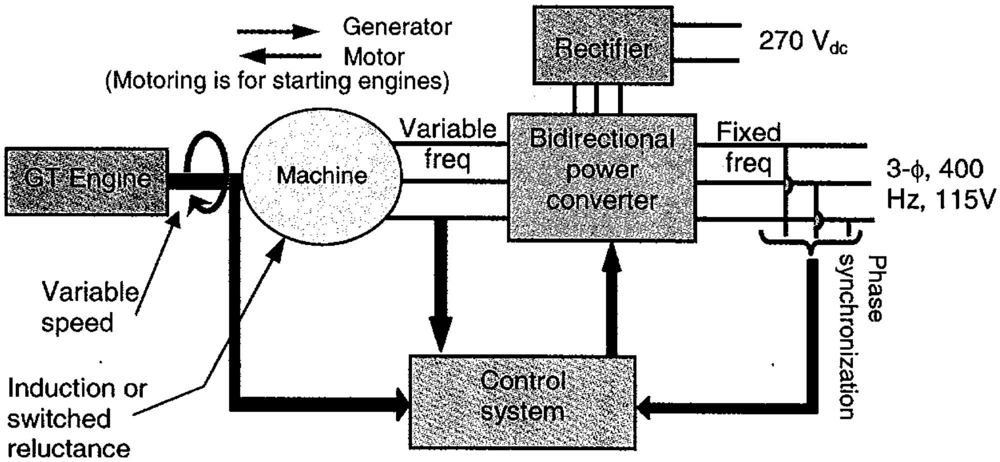

Fig. 9. Aircraft 400 Hz VSCF electric power generation system

SYSTEM LEVEL INTEGRATION

The proposed power system will consist of rotating and static, as well as ac and dc types of equipment both at the source and the load. For example, a fuel cell generating source, which has no rotating parts, will be interfaced with the ac side with a power electronic converter. On the other hand a synchronous machine is a complex rotating machine that depends on electromechanical principles to develop both active and reactive powers, but may or may not require a power electronic interface to the rest of the network depending on whether a voltage and/or frequency conversion is desired.

Fig. 10 shows the overall power system designed for lunar/Mars habitat. It consists of both an AC and a DC ring bus structures with generation sources located on both subsystems. The AC bus will have primary generation, while the dc bus hosts the backup/standby generation. Both ring bus structures allow isolation of specific segments for fault clearing while providing power to all load distribution centers from either the primary or the standby sources.

Generation

Fig. 11 shows the AC power generation and transmission at 400 Hz frequency. The solid state bus tie (SSBT) is normally open. It is closed only when any one of the sources is lost. Fault tolerance is added by providing a tie between the two sources by means of another SSBT. The solid state breaker (SSB) operates must faster than its mechanical counterpart. The assumption is that power can be generated close to the habitat and thus long transmission line will not be needed. Power may be generated at a variable frequency at the source by means of a switched reluctance machine (SRM) or a double-fed induction machine (DFIM) while making use of the concepts of power electronic building blocks (PEBB) [35].

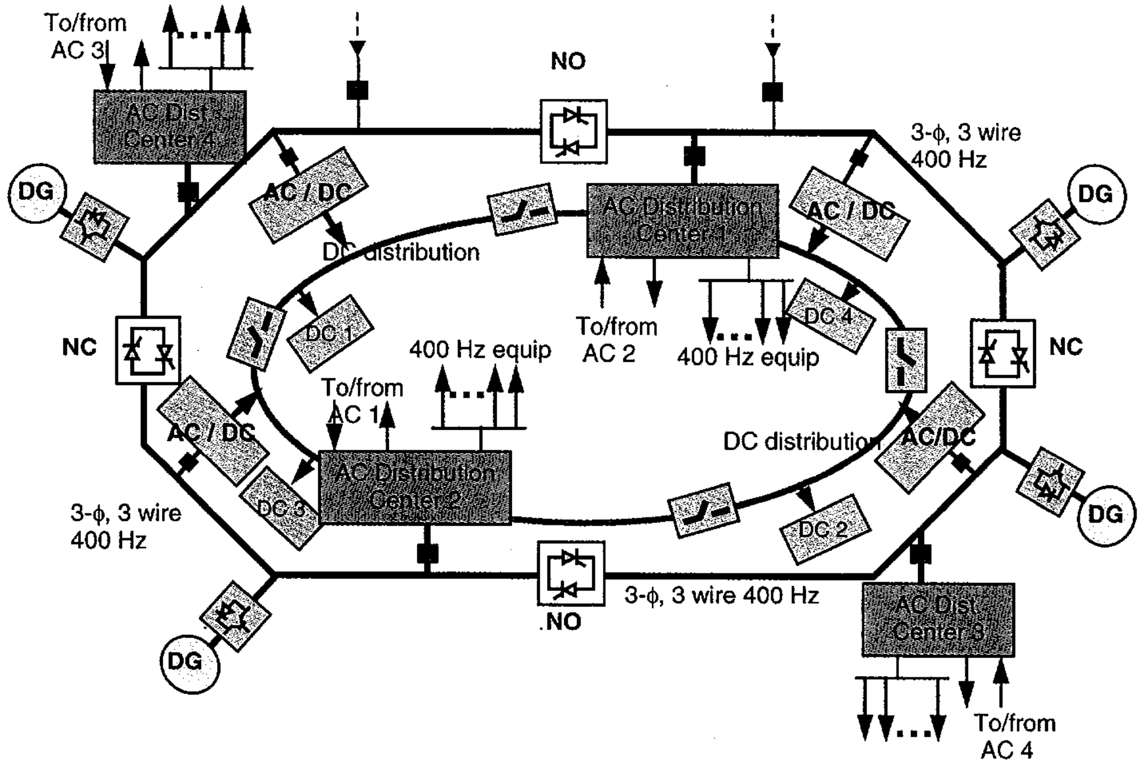

Fig. 10. The overall power system for lunar/Mars habitat

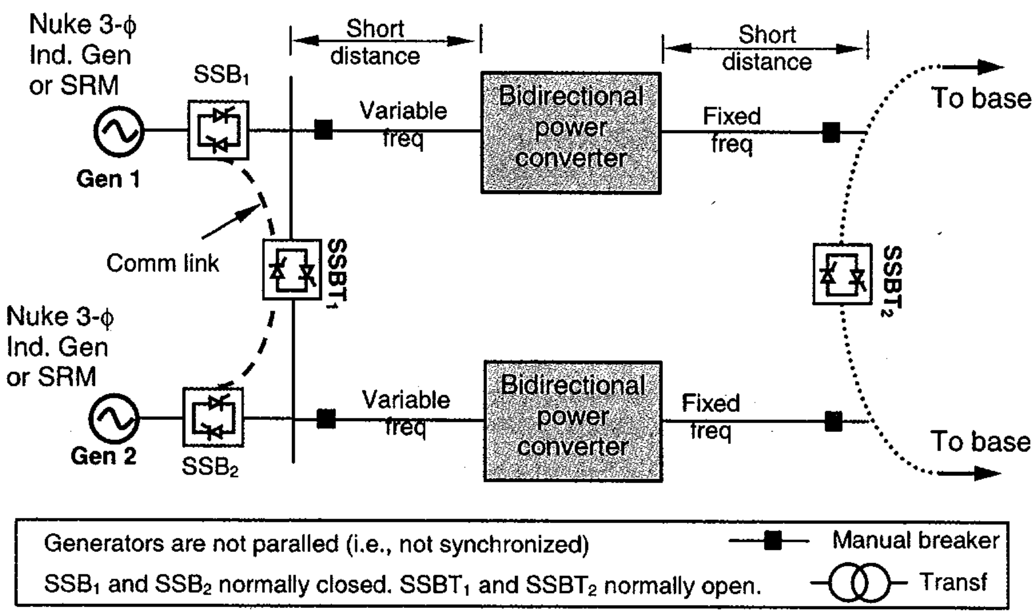

Fig. 11. Nuclear-based AC power generation and transmission using SRM and solid state converters.

CONCLUSIONS

Terrestrial and aircraft power system architectures are two of the most successful applications of engineering innovation and ingenuity that are at the core of the comforts and conveniences of modern living. They have both evolved over several years of design changes and, although neither is perfect, they operate very well under a great deal of uncertainty in operating conditions. On the other hand, the power systems on board the Shuttle Orbiter and the International Space Station offer the very best in power system technology, considering the enormous constraints of space travel and limitations in fuel supply. Incredibly, the technological challenges in building power systems for future space exploration and habitation on the Moon or Mars will be multiplied many fold. The requirements for applications in space beyond low earth orbit (LEO) as compared to terrestrial applications are listed below:

- Build N-redundancy for safety, fault tolerance and service continuity. N is a number much greater than that used on terrestrial system where N is usually 1 or at most 2.
- Build modularity for easy maintenance and repair. Terrestrial systems are inherently non-modular.
- Build distributed architecture for fault tolerance. This is in stark contrast to the centralized nature of terrestrial systems.
- Control and protection devices should be fast. Although protection devices for terrestrial applications are becoming faster now due to application of power electronics, the fastest device operates at about ¼ cycle of 60 Hz frequency. Space applications will most likely use 400 Hz frequency and thus will require faster protection devices.
- Avoid catastrophic wiring failure at all cost for safety. Conductor failures are common on terrestrial systems due to lightning, ice and wind.
- Total loading on the system should be monitored and kept within bounds. The allowable band is much more flexible on terrestrial systems because of a stiffer source.
- Overcurrents and overvoltages should be avoided. Again, the allowable band is much more flexible on terrestrial systems.
- Conductor wires should be as short as possible to avoid voltage drops and reduce weight. On terrestrial systems, high voltage transmission lines run for hundreds of miles.
- The system must have reserve and emergency backup for long durations. This is similar in nature to terrestrial systems.
- Generate power at higher voltages to reduce current and size/weight. Although the philosophy is similar for terrestrial systems, there is a limit to the highest voltage levels that may be used because of the prospect of corona occurring in outer space at lower levels.
- Use of power electronics for high density power systems. Generic terrestrial power systems do not generally use power electronics to generate or distribute power barring for a few exceptions.
- Use electromechanical systems utilizing permanent magnet (PM) machines to reduce weight. Generators on terrestrial systems use mostly synchronous machines where both the stator and rotor have windings.
- Use power electronic converters for voltage regulation. On terrestrial systems, automatic voltage regulation at the source is done by an exciter connected to the rotor circuit of a synchronous generator. Since a PM machine will be used for space application, power electronic conversion is required to bring about a similar effect.

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