"Important System Design Concepts for a Modular DC Rack Power System featuring a Single Phase 100A, 48V Switch Mode Rectifier"

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Abstract

The size reduction which has occurred in power conversion equipment due to the introduction of high frequency switching techniques has enabled the introduction of versatile and modular approaches to the system design of DC power plants for Telecommunications applications requiring very high reliability DC power.

It is argued in this paper that many requirements often written into DC power supply equipment specifications are irrelevant or of low priority when applied to the new technology. They are typically left-overs of the needs which were relevant to the older phase-controlled equipment.

Issues regarding the use of circuit breakers, forced convection, extensive alarm annunciation and single as opposed to three phase input are explored and tested for their relevance.

An example of a single phase input, fan cooled, 100A, 48V rectifier/battery charger designed with these principles in mind is described to demonstrate the very significant gains achieved in size and cost.

Introduction

People in all walks of life are now becoming aware of the mind-boggling revolution which is happening in telecommunications. Optical fibre networks, satellite communications links, cellular mobile telephone networks, facsimile machines, modem hook-ups between computers in different continents; all these different communication tools have come into existence and common usage in the last ten years or so.

One of the consequences of this revolution is that it is becoming very difficult for communications systems designers to predict with any accuracy the power requirements of the networks in the short to medium term let alone the long term. Fortuitously, or perhaps because of the increasing need, a similar revolution has occurred almost in parallel in the design of DC power supplies. In particular, the miniaturisation of the equipment has allowed and encouraged a modular approach to evolve, leading to much easier expansion and reconfiguration of DC power systems as the needs change over time.

With the changing design approaches made possible by the new high frequency power conversion technology has come a number of important differences in the way such modular systems are designed and managed. Unfortunately, in many instances, the DC power systems are still being specified by engineers who have not fully grasped the significance of the changes which have occurred and so are imposing unnecessary and harmful restrictions on the designers and manufacturers of these new generation power supplies to the detriment of both the manufacturer and end user.

This paper attempts to highlight some of the changes that have occurred and which should be considered by system designers when they are writing specifications for DC power systems.

Maintenance Philosophy

The previous generation of DC power supplies, consisted typically of large phase controlled thyristor rectifiers. The normal practice was to specify a rectifier size which would adequately serve the needs of a particular exchange for the ensuing 20 or 30 years. There would typically be two rectifiers operating in parallel with each one being capable of carrying the full load.

If a problem arose with either rectifier, a technician would come to the site and repair the faulty unit. With rectifiers weighing several hundred kilograms, there was no other choice. This lead to the desirability, indeed the necessity for the original system designer to specify carefully the rectifier in detail ranging from how wires were to be labelled, how the operating and maintenance manual was to be written, to how many and what alarms were to be included etc. All these measures were included in an attempt to make it possible for service personnel to be able to repair the unit when the need arose.

The situation has now changed dramatically in two important ways: Firstly, the size of the power modules is such that they can readily be returned to the manufacturer for repair; secondly, the complexity of the units is such that on-site repair is difficult, if not impossible.

These two factors in turn impact on two aspects of system management and design.

Firstly, it no longer makes economic sense for a telecommunications company to have a fully fledged service and repair team to repair the various types of DC power supplies which may be in use within the company's plants. The manufacturer has all the necessary equipment and technical personnel required to repair faulty units. Maintenance can thus be restricted to the module swapping level. If a module is faulty, the operator only needs to unplug it and replace it with a spare one and send the faulty unit to the manufacturer.

Secondly, and mainly as a consequence of the above, there is no need to specify the rectifier design in any detail. The rectifier should be treated as a power converter module which either works or does not work. A single OK/NOT OK indicator is all that is needed. It does not greatly help the operator if a myriad alarms indicate what may possibly be wrong with the unit.

Similarly, it does not help greatly for the manufacturer to know which particular alarm was up when the rectifier was replaced. In many instances, the operator may be less than careful in recording the observations, so it is normal for the repair technician to not assume anything and simply subject all the individual subassemblies within the rectifier to individual testing until the fault is located and repaired.

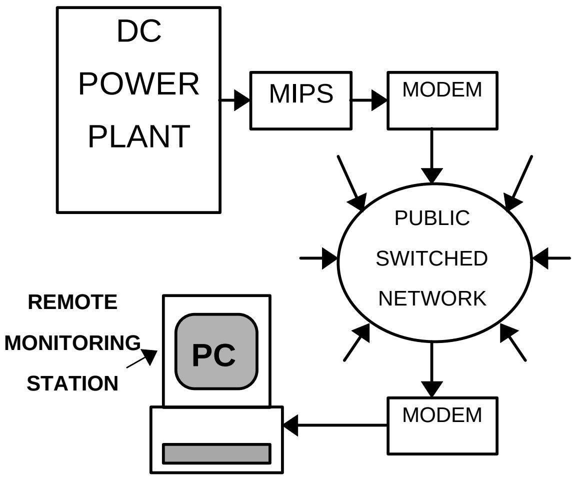
It is clear that by taking this approach to its logical conclusion, potential savings and reliability gains are possible through significant simplification of the circuits.

Remote Monitoring and Control

Also impacting on the maintenance philosophy is the relative ease with which microprocessors can be included in equipment and with them the possibility of implementing monitoring and control of the power plants from a remote location by means of a PC.

It is equally important to ensure that the monitoring and control functions are not lost if the commercial AC power at the power plant site being monitored is temporarily lost. To overcome this problem, a Modem Interface and Power Supply unit (MIPS) was designed to interface between standard commercially available modems and the plant monitoring equipment's RS485 digital port.

The unit operates off the Rectifier/Battery DC bus and has a flyback SMPS which supplies power to its own RS485/RS232 converter as well as 9 or 12Vdc for the external modem. Any interruption of AC power will thus not interfere with the digital link to the remote monitoring PC.



Remote Monitoring Arrangement

A set-up as shown above enables a telecommunications company to have a single monitoring and control centre to supervise power plants throughout a region or country.

An experienced technician/engineer can regularly access different sites to check on performance and/or problems that need attention. Alternatively, the system can rely on individual units logging on to the central remote monitor to report any alarm or fault condition.

The operator then has the option of accessing the power plant in question and deciding on whether there is a real problem and the unit/units need changing or the problem is only temporary (e.g. AC power failure) and will eventually return to normal. In the event that a unit appears to be faulty, a phone call to a local operator can result in the unit being replaced by a spare and the faulty unit being despatched to the repair centre.

A further major advantage of this systems management approach is that battery management and maintenance can be more effective through careful and uniform setting of operating parameters such as float voltage and equalisation cycles. Any decision to change one or more of the operating parameters becomes a single and simple task by exercising a global command facility provided.

With such features and equipment facilities available, there is no question that system operators need to look critically at their maintenance practice.

Single phase versus three phase

Of considerable importance to the final outcome in terms of overall system cost, modularity, reliability and designability is the question of whether a unit should be single or three phase input, and, if three phase, whether it should have a neutral available or not.

There are many DC power supply system specifications around which clearly spell out up to what current rating the rectifier shall be single phase, with three phase being mandatory above that point.

The reason for having such a limitation is most often historical, the specification usually being derived from an original specifically aimed at thyristor phase controlled models.

The most important reason for reviewing this subject is the ever increasing requirement for sinusoidal input, power factor correction circuits. At this juncture, the most common circuit used to achieve this feature is the Boost circuit operated in continuous current mode followed by some kind of DC/DC converter stage. For various reasons, this topology is rugged, reliable and requires relatively few components, but must be used with a single phase supply.

Although there are other topologies including some which employ a single power switch for both the input and DC conversion stage [3], none have proved to be the equal of the Boost/ DC converter two stage combination in terms of cost, performance and reliability.

When the input power supply is three phase, achieving the same result requires a significantly more complicated circuit.

One topology that has been used commercially successfully to date [2],[3], utilises a buck circuit with six power switches controlled in such a way as to achieve both regulation of the high voltage DC bus ahead of some DC/DC converter, and sinusoidal current in all three phases.

This three phase buck circuit is relatively complicated and has a relatively large number of components when compared to a single phase input boost circuit stage.

For example:

- Six power switches instead of one
- Six isolated gate drives instead of one non-isolated gate drive
- Six snubbers vs. one
- Three EMI filter components per stage instead of two
- Three pole instead of single pole circuit breaker or fuses
- Typically fifty per cent more wiring in the input circuit
- Much more complicated switch control algorithm, usually requiring a microprocessor controller circuit
- More components in the input AC voltage High/Low detecting circuit

These considerable differences are reflected in differences in cost as well as size and to some extent reliability in favour of the single phase circuit.

A further difference is that the boost circuit is more efficient under normal conditions as the power switch is on and conducting the input current for only 20-25% of the time compared with the buck switches which are on for 75-80% of the time under nominal AC voltage conditions.

Given these considerable differences in favour of the single phase boost circuit, the question arises as to up to what power level it can be used to. Given the input currents involved and maximum sizes of PCB mounting relays available (for AC isolation and inrush limiting circuit), 100A, 56V DC appears to be a practical maximum limit for single phase sinusoidal input SMRs (Switch Mode Rectifiers), yet most specifications only allow single phase units to a power level of approximately 3 kW - (50A/48V).

With the advent of modular rack power systems employing many SMR units, there appears to be no valid reason why units up to 100A, 48V rating should not be permitted.

One disadvantage of single phase units is the extra cost incurred in supplying the neutral conductor and, to a lesser extent, the higher cable rating required when the number of units is not an even multiple of three.

This translates into a cable cost difference in favour of three phase units, but is typically much less than 1% of the total cost of a Rack Power System.

Another possible consequence arising from the single versus three phase question is the sizing of the stand-by generator when this is applicable.

There are two factors which counteract the possible need to make the plant bigger in the case of single phase units.

Firstly, it is normal practice to size the stand-by generator at least 25% or so above the required kilowatt rating to allow for derating of the engine due to ageing as well as for low temperature start up operation. When the engine is cold, its kW rating is 20% or so lower than when it is at normal running temperature.

Secondly, virtually all commercial alternators are designed to operate at a power factor of as low as 0.8. This means that the current in any one phase can be 25% higher than that corresponding to a resistive load, provided that the total kilowatt rating is not exceeded.

Taking as an example four 100A, 56V units, the kilowatt requirement is 4 x 5.6 = 22.4kW, thus a unit with a minimum rating of 1.25 x 22.4 = 28kW (approximately) would be chosen. In practice this would be a 30kW / 37.5kVA unit. For 380V AC, this means a current rating of 57A which is more than the 54A which is required for the one phase which has two units operating on it. Note that with three phase units, the same size stand-by unit would be chosen because of the same kilowatt requirement.

Finally, an important advantage of single phase units is that in the event that one of the phases fails about two thirds of the full power rating, depending on the number of units powered by the line which has failed, is still available. With few exceptions [5], most three phase units are designed to shut down in such a situation.

The quite considerable saving in parts count, and consequently in cost and size and the improved reliability and to a lesser extent efficiency, dictates that larger single phase units than are being allowed at present by most specifications should be considered.

Circuit Breakers

Many Specifications call for circuit breakers to be included in the SMR input and output terminals. There are some strong arguments for an alternative approach.

Input Protection

The only time that an input CB in a correctly designed SMR trips is under fault conditions. When this happens, the most likely problem is a failed semiconductor, usually one of the power switches. If the CB is turned on again, the only outcome is more damage internally, such as destroyed PCB tracks.

It thus follows that replacing the CB by fuses is a much better option because, if the fuses fail, the only correct course of action is to replace the SMR and send it away for repair.

The function of turning on and off the SMR can be carried out by an electronic switch which can control the relays (or other devices) in the inrush-limiting circuit.

The total isolation of the unit should then be done at the source of the AC power, such as an AC panel at the top of the rack which has a CB for each SMR.

Output Protection

Protection is required at the output for two main reasons:

i. to protect the individual SMR against accidental reverse polarity connection;

ii. protection of the system against the SMR output circuit failing into a short-circuit condition.

In both cases a fast fuse is a better form of protection as its "let-through" energy is less than that of a CB.

A switch function (which is provided by a CB) is often specified in order to allow “hot” connection of the unit to the DC bus. The CB is closed only after the unit output voltage is at its working level.

An alternative approach is to include a “pre-charging” circuit which utilises a small auxiliary connector which mates with the output bus before the main connector.

Removing both the input and output circuit breakers from an SMR can make a very significant reduction in the cost of the unit as well as enhancing its reliability and efficiency.

Forced versus Natural Convection cooling.

The most obvious incentive for utilising fans (forced convection) in SMRs is to reduce the size of the heat sink in particular.

There are, however, some other benefits which are less obvious:

1. The temperature of some components within the unit which are not mounted on the heat sink can be maintained at a lower temperature.
2. In naturally convected units the temperature of the highest unit in a rack of units can be considerably higher than the unit which is lowest on the rack. In particular, it is usually necessary to have varying spacing between units at different heights in the rack. Needless to say, the overall packing density is greatly reduced.
3. At low power levels, the temperature in a fan cooled unit drops quite dramatically and tends to be lower than for a natural convection cooled unit. As the MTBF and end-of-life of all electronic components increases with decreasing temperature, this

can be a significant factor in favour of fan cooling.

The disadvantages of having fans are the extra cost, acoustic noise and the reliability factor.

Cost

In most instances, the cost of the fan can be justified by the reduced cost of the heat-sink and case. In addition, the much greater rack packing density results in much greater savings when viewed from a systems basis, particularly in large systems requiring multiple racks.

As an example, a typical system made up of 100A SMRs which are natural convection cooled would require one rack for every 4 or perhaps 5 units; i.e. 400-500A per 19" rack.

Using the unit shown below, 2000A per rack is obtained. The reduced cost of racks, associated bus-bar interconnections and exchange floor area is very considerable indeed.

Acoustic Noise

Fan cooled units tend to be noisier than naturally cooled ones due to the additional noise created by the fan.

For large power systems in particular, the extra noise is not a practical problem, as the units are typically located in a power room together with batteries.

Reliability

The reliability of fans has increased markedly with the introduction of brushless DC fan technology.

The reason for this is two-fold:

i. The very simple electronic inverter which replaces the brushes is orders of magnitude more reliable;

ii. The lower power dissipation of the inverter/permanent magnet combination leads to lower temperature operation.

In a discussion of reliability of the fan, it is important to be clear about which aspect of the total reliability characteristic behaviour one is referring to in relation to the normal "bath-tub" model used to discuss this topic.

The typical "bath-tub" behaviour has three important time/failure areas namely: Infantile, Random, and End-of-life failures.

According to the manufacturer and from actual field experience, the infantile and random failure rate for the fans is almost negligible, assuming they are operated in a reasonably clean environment.

Over a period during which the authors were involved with a particular product which utilised the same type of fans, at least 6000 fan-years were recorded with no replacements required. This represents a virtually negligible random failure rate.

However, it is well known that the fans have a very finite and fairly well defined end-of-life due to the loss of bearing grease through evaporation.

The rate of evaporation of the grease depends on the temperature of the grease, which in turn depends on various factors such as :

- Temperature of the air flowing around the fan
- Temperature of the winding, which in turn depends on the voltage applied
- The speed of rotation

The best way to minimise the air temperature around the fan is to use the fan in a "pushing" mode rather than a "sucking" mode. This way the air flowing past the fan is at ambient temperature. This arrangement is much preferable to the alternative one in which air is sucked through the unit and is therefore hot when it flows past the fan.

The other two factors are not very strong and have a second order effect on the end-of-life figure.

For the PAPST 8412 12V DC fan used in the RT1S100 unit described below, the life expectancy is given as follows:

Service Life at 75 ^{O}C - 25,000 hours

Service Life at 40 ^{O}C - 70,000 hours

If an average yearly temperature of 35^{O}C is used, the expected end-of-life is in excess of 80,000 hours (9 years).

Single Phase input 100A, 48V Rectifier/Battery Charger with lid removed

A High efficiency 100A Single Phase Rectifier

The rectifier, a photograph of which is shown above, is an example of what was achieved by putting into practice the principles outlined above.

It is based on a 70A 48V rectifier circuit comprising a Boost stage with lossless snubber and half bridge converter circuit published at the 1993 INTELEC conference [4]

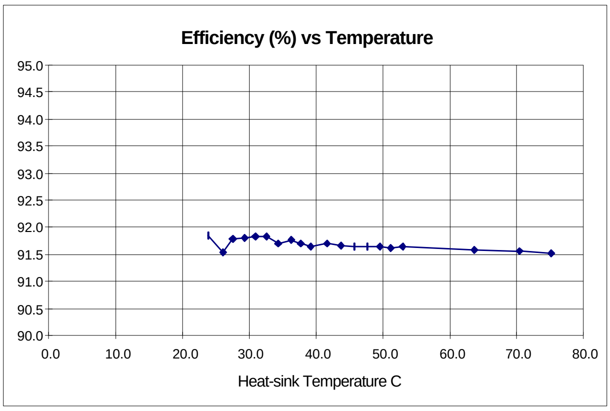
The circuit was upgraded in terms of power rating of the various components and an extra MOSFET placed in parallel with the existing ones. Of course the mechanical layout was completely altered to achieve a low profile horizontal aspect as opposed to the vertically arranged heatsink of the original 50/70A unit which was designed for natural convection at 50A.

The principal features of the circuit are:

* Parallel IGBT/MOS power switches used;
* Lossless snubber circuit used in the Boost stage to improve efficiency;
* Efficiency at full load >91% even at the maximum temperature;
* Highly compact: 2U height, 19″ rack width, 400mm depth; 20 can fit in a 2200mm rack;
* Microprocessor interface allows monitoring and control from a remote location via modem and PC;
* Weight less than 17kg;
* Input and output fuses; CBs are optional;
* Unity Power Factor and input current harmonics comply with IEC555-2;
* Full surge voltage protection to ANSI C62.41-1991;
* Fully modular with plug-in connections at the rear of the unit;
* Up to 110 units can be paralleled with active current sharing under the control of a Control and Supervisory Unit (CSU); defaulting to passive current sharing in the event of a fault in the CSU;

One of the important advantages of the topology used and in particular the IGBT/MOSFET combination is that the efficiency does not drop dramatically with temperature as it tends to do in all MOSFET-only schemes.

With this design, as shown in the plot below, the efficiency drops by less than 0.3% as the heat-sink temperature changes from 20°C to 75°C. The reason for this behaviour is that the forward voltage drop of the IGBTs during the conduction period does not increase significantly with temperature increase. In some types of IGBTs it actually decreases as temperature increases. This is in sharp contrast to MOSFET-only designs in which the power dissipation due to the MOSFET forward drop can double over the operating temperature range.



Change of Efficiency as a function of Temperature

Another important feature which results from using the particular topology chosen is that the maximum efficiency is attained at approximately 70% of full output current as shown in the plot below. This is the typical output current at which most of these DC systems are designed to work at when batteries are not being charged. This is typically more than 99% of the time.

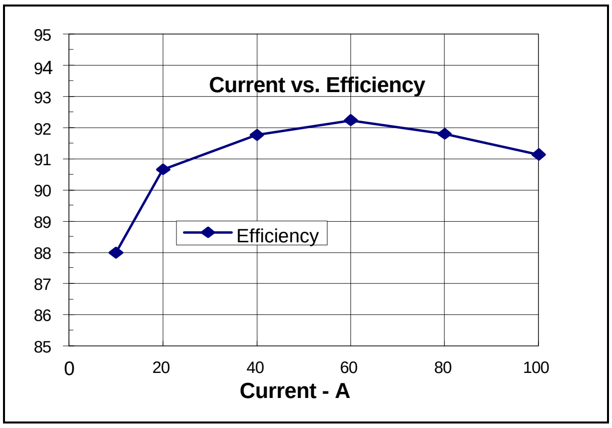


Fig. 2 Efficiency of 100A Rectifier

It should be noted that the efficiency curve is for a unit complete with EMI filters, connectors etc. ready for insertion into a 19″ rack power system as shown below.

DC Rack Power System

When used with the Rectifier Technologies Control and Supervisory Unit (CSU) a very flexible DC Rack Power system, as shown in the figure below, can be configured to satisfy the most sophisticated battery and load management regimes.

This includes features such as:

* Temperature compensation of Battery Float Voltage;
* Automatic or manual equalisation of batteries;
* Individual temperature and current monitoring of up to four battery banks;
* Battery charging current limit;
* Automatic or manual Low Voltage Disconnect Switch control;
* RS-232 local communications port for use during maintenance and /or commissioning which enables downloading of all operating parameters from a PC;
* RS-485 remote communications link for remote monitoring and control via a PC or modem and public switched network for intra and inter country maintenance;
* Auto-dial facility for remote site automatic monitoring;

The small size of the SMRs means unprecedented power density.

A complete Rack Power System comprising an AC distribution module, CSU and 20 RT1S100 rectifiers, has a rated output of 2000A and can supply 2200A during the recharge cycle due to the availability of a 110A current limit up to an output voltage of 51VDC.

A 300A 3 Phase Rectifier

The topology and resultant circuit was extended to its limit in terms of maximum current per module and minimum cost per amp by combining three of the 100A modules into one metal enclosure, saving some common circuit modules in the process.

The resulting 300A rectifier is 6U high and is the most compact 300A unit available commercially. It is particularly aimed at large Central Office power plants.

Although quite heavy at under 45kg, it is still manageable by two people, although a lifting device is a safer alternative for installing the units in a rack.

The normal model requires a Neutral, but for those applications in which a neutral is not supplied for whatever reason, techniques are available [4]for balancing the input currents in such a way that the neutral is not required.

In our view, the extra complication is not warranted by the small saving in copper in the AC cables.

Conclusion

Some issues relating to the content of specifications for DC power conversion equipment have been examined.

It is asserted that in order to fully exploit the size and reduction made possible by HF power conversion techniques, circuit breakers can be replaced by fuses, forced convection cooling in place of natural convection cooling and a minimal set of alarms display.

This leads to a change in maintenance philosophy to one of unit replacement on site by relatively untrained operators with the repair of the faulty units effected by the equipment manufacturer.

An example of a rectifier/battery charger which was designed to comply with these principles has been described, together with the derivative product, the only commercially available Switch Mode 300A, 48V rectifier/battery charger.

2000A Rack Power System

The very high power density achieved for both of these products demonstrates the value of the principles described.

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