A NEW DIGITAL CONTROL ARCHITECTURE FOR BATTERY PLANTS

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***Abstract*: We present a new control architecture for battery plants that simultaneously allows precise plant-voltage control and current sharing. Limitations of earlier approaches are also discussed. A digital implementation of the new control architecture provides robustness and flexibility and enables reliable powering under a variety of operating scenarios.**

I. Introduction

Today, distributed powering architectures are successfully employed in a wide range of communications applications to provide high availability in a cost-effective manner. Since availability of commercial AC is often the biggest factor affecting the availability of power, the use of batteries to provide energy reserve has become standard practice throughout the world. Thus, battery plants, which are formed by combining AC/DC rectifiers whose outputs are connected in parallel with the batteries and the load, play a crucial role in powering modern communication networks.

Over several decades, battery plants have been improved in many ways. These improvements have focused on improving the overall availability of the plant, reducing the size, decreasing maintenance and lowering the cost. About two decades ago, switchmode rectifiers were first introduced into battery plants. These were smaller and more efficient than the SCR-based and ferroresonant-transformer-based rectifiers that were being used at that time. Around the same time, microprocessors were also introduced into battery plants [1-3], because they provided flexible functionality without requiring hardware changes. Today, microprocessors are routinely used in battery plants, both in the plant controller and in individual rectifiers where they are used to perform numerous control and alarm functions.

This paper focuses on a control architecture that provides precise plant voltage control as well as being flexible enough to enable different methods of controlling the current or thermal stress among the paralleled rectifiers. Section II starts with the description of a conventional plant and an analysis showing the limitations with respect to setting plant voltage. Specifically, we will show that when individual reference voltages in each rectifier are used, the overall plant voltage is approximately the average of the individual reference voltages. The new control architecture is described in Section III along with advantages of the new approach. Digital implementations of the new control scheme are also discussed. Section IV discusses some variations of the new control architecture that enable such functions as limiting charging current during a battery recharge and controlling current between rectifiers to equalize thermal stresses. Some of the key features that are enabled by using the digital control architecture are outlined in Section V. Conclusions and a summary are presented in Section VI.

II. Conventional Approach

Figure 1 shows the block diagram of a battery plant depicting the connections of the rectifiers, batteries, load and the controller. The main subsystems in the plant are:

1. The rectifiers that convert AC to DC and have their outputs connected in parallel to provide redundancy.
2. One or more strings of batteries connected in parallel with the rectifier outputs, to provide energy reserve to power the plant in the event of an AC failure or when not enough rectifiers are available to power the load
3. A plant controller, that monitors and controls plant operation and provides an interface to the external world.
4. Interconnects and distribution used to provide fault isolation and protection.

The conventional control architecture of the plant shown in Fig. 1 is described by Fig. 2. In this scheme, each rectifier has a reference voltage, shown as V_{REFj} for rectifier j. The plant voltage v_L and average rectifier current I_{AV} are fed to each rectifier as shown in detail for rectifier j. An analog loop is used to maintain current

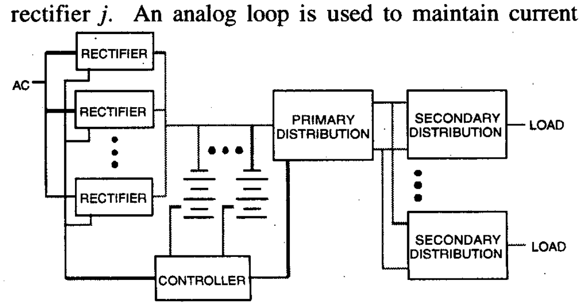

Fig. 1. Block diagram showing a typical battery plant.

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sharing by comparing the current of each rectifier to the average current, and using the resulting current-share error to offset each rectifier reference voltage V_{REFj}. This results in a modified reference voltage V_{Rj} in each rectifier that is then compared to the plant voltage v_L that is sent to all rectifiers. The high-gain voltage-control loop in each rectifier tries to regulate the scaled plant voltage (through block B_j) to be equal to the modified reference voltage V_{Rj}. For low frequencies, where the gain of the voltage-control loop in each rectifier is high, the following equation can be used to describe the relationship between the relationship between each individual reference voltage and the plant voltage for $j = 1,..,N$.

$$V_{REFj} - M_j\left(I_{AV} - I_j\right) = B_j v_L \quad (1)$$

This equation can be rewritten as follows:

$$I_j = \frac{B_j v_L}{M_j} - \frac{V_{REFj}}{M_j} + I_{AV} \quad (2)$$

The sum of the individual rectifier currents is the total load current, and the following equation can be written:

$$\sum_{j=1}^{N} I_j = \sum_{j=1}^{N} \frac{B_j v_L}{M_j} - \sum_{j=1}^{N} \frac{V_{REFj}}{M_j} + \sum_{j=1}^{N} I_{AV} \quad (3)$$

Since the sum of the individual rectifier currents (ΣI_j) is the same as the sum of the average currents (ΣI_{AV}), (3) simplifies to

$$\sum_{j=1}^{N} \frac{B_j v_L}{M_j} = \sum_{j=1}^{N} \frac{V_{REFj}}{M_j} \quad (4)$$

With the simplifying assumption that the rectifiers are identical except for the reference voltages (which means that the quantities B, and M are the same for all rectifiers), we obtain the following relationship between the individual reference voltages and the plant voltage:

$$v_L = \frac{1}{BN} \sum_{j=1}^{N} V_{REFj} \quad (5)$$

Equation (5) shows that in the conventional battery plant, the plant voltage v_L is an average of the individual reference voltages (V_{REF1} to V_{REFN}) in each of the rectifiers.

In most battery plants, the batteries are float charged and hence the plant voltage directly influences the float current. From an electrical perspective, batteries have very small impedances, and hence small changes in float voltage can cause large changes in float current. Excessive float current in a fully-charged battery can cause overheating, excessive gassing and lead to greatly reduced battery life. Thus, the ability to precisely control battery plant voltage means that tighter control of battery charging can be maintained. The benefits of precise plant voltage control are even greater when VRLA (Valve-Regulated Lead Acid) batteries are used, because they are less tolerant to overcharging than flooded lead-acid batteries.

Since in the conventional approach the plant voltage is an average of the individual rectifier reference voltages, setting plant voltage relies on potentiometers or similar controls in each individual rectifier that are adjusted during installation to set the plant voltage at the required level, usually at the recommended float voltage. When

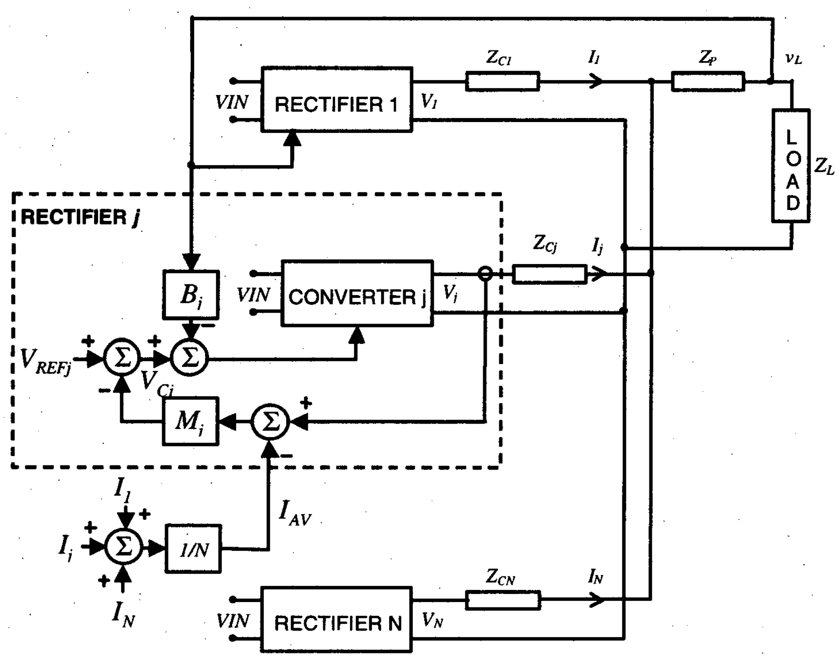

Fig. 2. Control architecture of a conventional battery plant.

the plant configuration changes, such as when rectifiers are added, removed or replaced, this installation procedure has to be repeated. Since this procedure is done manually, plant commissioning, installing upgrades or rectifier replacement involves additional installation time and expenditures. In addition, variations due to load current changes, temperature changes or battery changes also require a periodic "tweaking" of the plant voltage to readjust it to the desired value.

III. New Control Architecture

A new control scheme [4], that provides automatic precise regulation of the plant voltage while simultaneously maintaining active current sharing among the rectifiers is shown in block diagram form in Fig. 3. Details are shown for rectifier j, all other rectifiers have the same structure. Each rectifier is shown connected through an impedance Z_{Cj} to a common interconnection point P, and then through the impedance Z_P to the load impedance Z_L. In a battery plant, the impedance Z_L represents the parallel combination of the battery and the actual load being powered. The impedance Z_{Cj} is typically the sum of the rectifier output impedance, output circuit breaker or fuse impedance and the impedance of the wires or bus bars used to interconnect the rectifier outputs. The impedance Z_P represents the impedance of the connections between where the rectifiers are connected in parallel to the battery. The plant voltage is usually sensed at the battery terminals, or when multiple strings are used, at the points where all battery strings are connected together. This voltage is sensed and compared to the plant reference voltage V_{DPV}, and the resulting error voltage is fed to each rectifier. In addition, the output current of each rectifier is sensed and the average value I_{AV} is calculated.

In each rectifier j, the output current of that particular rectifier I_j is compared to the average output current I_{AV} and the resulting error signal $I_j - I_{AV}$ is processed by the block M_j. In addition, the plant error voltage $(V_{DPV} - v_L)$ is processed by the control block K_j. The two processed error signals $K_j(V_{DPV} - v_L)$ and $M_j(I_j - I_{AV})$ are combined and compared with the fixed local reference voltage V_{REFj} to generate the reference voltage V_{Cj} for the output-voltage-control loop in the rectifier. The rectifier output voltage is sensed and processed by the control block B_j and the resulting signal is compared with the signal V_{Cj} to create a signal that then generates the duty cycle of the converter j. This control structure provides the following functions:

- The overall plant voltage is regulated to the single reference value V_{DPV}. This allows precise control of the plant voltage. In particular, during initial commissioning of the plant, or when rectifiers are added or removed, or other plant changes are made, no readjustment of individual rectifier reference voltages is necessary. Note that the reference voltage V_{DPV} can be made adjustable to accommodate different plant voltages for conditions like "boost" and "equalize".
- Each rectifier maintains its output current very close to the average output current I_{AV}, thus ensuring

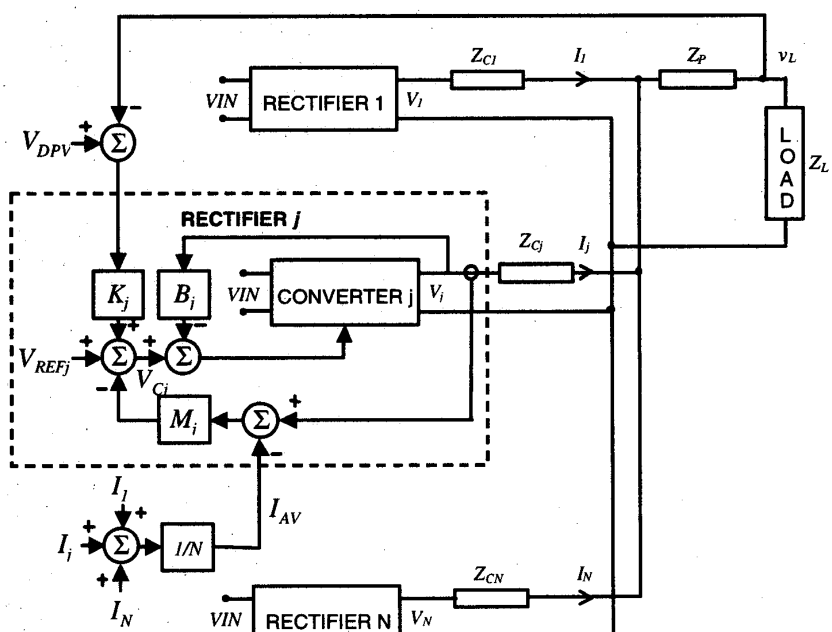

Fig. 3. Block diagram showing new control architecture used to provide precise plant voltage control along with current sharing among rectifiers.

current sharing among rectifiers.

- In the event of failure of the overall plant voltage-sensing loop, each rectifier regulates to the local reference voltage V_{REFj} and the voltage at the load is now an average of the individual reference voltages. Thus the fault-tolerance characteristics of earlier control strategies that required adjustment of individual rectifier reference voltages is retained.

A digital control implementation of the scheme shown in Fig. 3, is shown in Fig. 4. The operation of the digital implementation is as follows:

1. The plant controller samples the plant voltage v_L and digitizes it through an A/D converter. Using high-precision A/D converters, it is possible digitize the plant voltage with great precision. For example, using a 16-bit A/D converter, the plant voltage can be digitized with a resolution of about 1.2mV.
2. Every rectifier samples its output current, digitizes it through an A/D converter and sends the information to the plant controller. This measurement is done at approximately the same time instant in each rectifier, so that all rectifiers are measuring their output currents at about the same time.
3. Using the output current information provided by the rectifiers, the controller calculates the total current put out by the rectifiers and the average output current by dividing the total rectifier current by the number of rectifiers. If rectifiers of unequal capacities are being used, the average can be calculated as a fraction of the rated maximum output current of each rectifier. This average current information is sent to each of the rectifiers.
4. The controller subtracts the measured plant voltage from the desired plant voltage V_{DPV}, and also sends the "plant error voltage" to each of the rectifiers.
5. In each rectifier, the current error signal is generated by subtracting the the average current from the current signal of that rectifier. This error is added to the plant voltage error to generate a reference control voltage v_{Cj} for each rectifier. Alternately, this combined error signal can be added to a reference voltage value in each rectifier that serves as the "local" reference voltage.
6. The control voltage is thus periodically adjusted to vary the output voltage of the rectifier. A conventional fast analog control loop in each rectifier regulates the output voltage to track the reference control voltage V_{Cj}.

The following equation can be used to describe the system between the *(n-1)*-th and *n*-th time intervals when the control scheme shown in Fig. 4 is used:

$$v_j(n) = v_j(n-1) + K_j\left[V_{DPV} - v_L(n-1)\right] + M_j\left[i_{AV}(n-1) - i_j(n-1)\right] \quad (6)$$

for $j=1, \dots, N$, with

$$v_L(n-1) = Z_L \cdot i_L(n-1) \quad (7)$$

Here K_j is the "plant-voltage proportional feedback gain" for the j-th rectifier, i.e. the quantity by which the plant error voltage is multiplied in each rectifier when the rectifier control input voltage is calculated. The quantity M_j is the "current-sharing feedback gain" for the j-th rectifier, i.e. the quantity by which the current-sharing

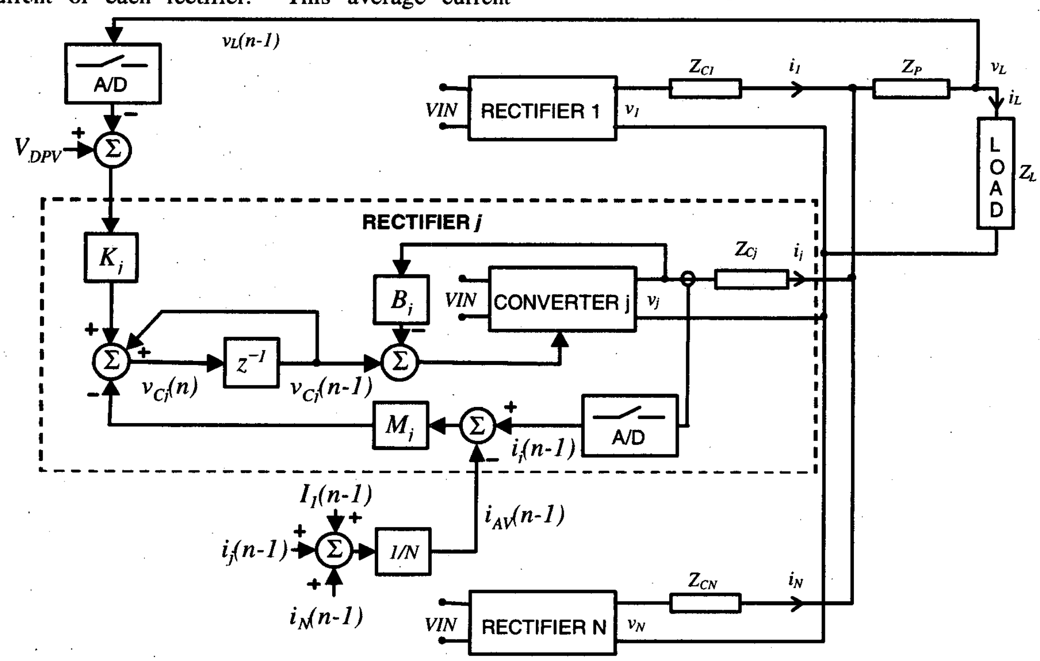

Fig. 4. Block diagram showing digital implementation of new control architecture used to provide precise plant voltage control and current sharing among rectifiers.

error (the desired rectifier output current minus its actual output current) is multiplied in each rectifier when the rectifier reference voltage is calculated.

If the gains K_j and M_j can be chosen to yield a stable closed-loop system, then for constant V_{DPV} and Z_L, the system will settle to a constant steady state. In this steady state, we see from (6) that (for $M_j \neq 0$)

$$\frac{K_j}{M_j}[V_{DPV} - v_L] + [i_{AV} - i_j] = 0 \tag{8}$$

Summing (8) over all j and noting that

$$\sum_{j=1}^{N}(i_{AV} - i_j) = \left(\sum_{1}^{N} i_{AV}\right) - \left(\sum_{1}^{N} i_j\right) = 0 \tag{9}$$

we find that

$$(V_{DPV} - v_L)\left(\sum_{1}^{N} \frac{K_j}{M_j}\right) = 0 \tag{10}$$

Hence, as long as $\Sigma(K_j/M_j) \neq 0$, we can conclude from (10) that $v_L = V_{DPV}$ in the steady state. In other words, simply ensuring stability of the system in Fig. 4 guarantees that the plant voltage v_L attains the desired value in the steady state, and the total load current is equally shared among the various rectifiers.

Implementation Guidelines

1. Plant voltage sampling occurs at a rate determined by the A/D in the plant controller, while sampling of each rectifier's output current occurs at a rate determined by the rectifier. In order to get accurate current information for calculating the average rectifier current, the output current of each rectifier must be sampled at the same instant. This can be done by having the plant controller issue a command to all rectifiers to simultaneously measure their output currents.
2. Generally, output current is digitized with a lower-precision A/D since current sharing need not be very precise. On the other hand, plant voltage, which needs to be regulated very precisely, must be digitized using high precision. Since lower precision means faster sampling, typically the current in each rectifier can be sampled at a much faster rate than the plant voltage. However, the output current of each rectifier also needs to be sent to the controller and an average current calculated and sent to each rectifier. There is therefore no advantage in adjusting rectifier reference voltage at a rate faster than either average current information or plant error voltage information is available.
3. The D/A in each rectifier, that converts the numerical value of the reference control voltage V_{Cj} to an analog voltage, has a finite resolution. This leads to an effective output voltage resolution, which given the output impedance of the rectifier and interconnection impedances, in turn translates to the smallest output current change possible. In general, the rectifier output impedance is the only impedance parameter that is under the control of the rectifier designer, since interconnection impedances will vary from plant to plant. Having a larger output impedance

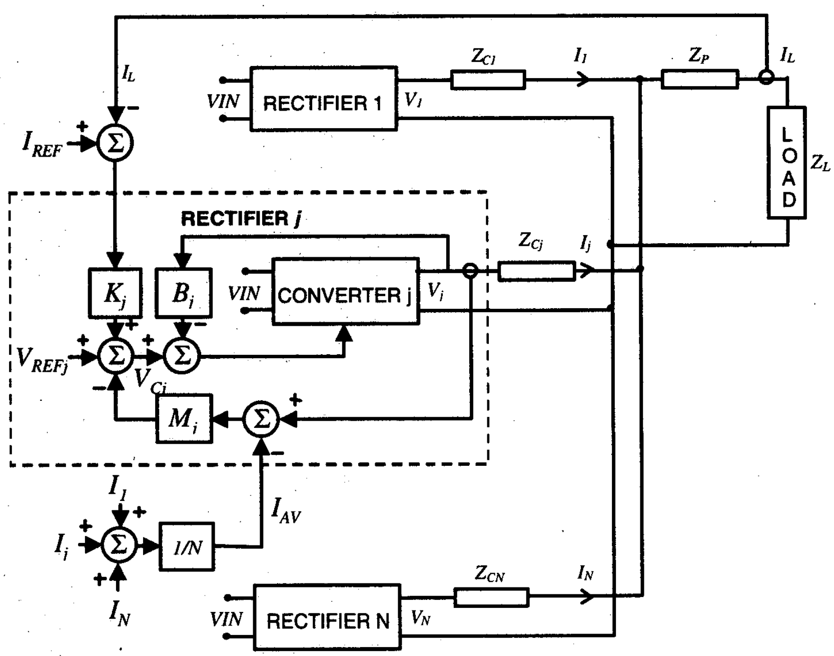

Fig. 5. Block diagram showing variation of the proposed architecture whereby current into a load can be precisely controlled while simultaneously maintaining current sharing among the rectifiers.

leads to a smaller value by which the output current can be changed, which in turn can lead to more precise current sharing. In actual practice, the output impedance of the rectifier has to be designed to meet the current sharing requirements and the allowed droop of the rectifier voltage.

IV. Variations Of The Control Architecture

Output-Current Control

Figure 5 shows a current-output version of the circuit shown in Fig. 4. Here, the load current I_L is sensed and compared to a reference signal I_{REF}, representing the desired load current level, to generate a common load current error $I_{REF}-I_L$. The common load current error $I_{REF}-I_L$ is sent to each of the rectifiers. In each of the rectifiers, the output current of each rectifier I_j is sensed and compared to an average output current I_{AV}. The resulting signal is processed by the block M_j to yield a current error which is added to the rectifier reference voltage V_{REFj} and the common load current error signal $I_{REF}-I_L$ processed by the block K_j to yield the converter reference voltage V_{Cj}. As an alternative to sensing load current, some other current such as battery current could also be sensed and regulated. This scheme could be used when battery plant loads or portions of the load need to be current limited, such as for example if battery current needs to be controlled during boost or normal recharge.

Constant-Current Mode

Another variation useful in controlling current into the load or a part of the load such as the battery, is to directly command the rectifiers to go into constant-current mode. This mode is typically implemented to allow such features as "current walk-in", where the rectifier is started in a current-limited mode and the output current is gradually increased in a controlled manner to the level demanded by the load. By commanding each rectifier to go into the constant-current mode and specifying the current level, the load current can be controlled. This scheme can also be used to control the current into part of the load, such as the batteries, by adjusting the total current so as to maintain the desired battery charging current.

Thermal Stress Share

A third possible variation on the new control architecture is to have the rectifier currents be shared among them so that the thermal stress in each rectifier is approximately the same. This can be done, by having each rectifier send back temperature information to the controller. The controller can then adjust the rectifier currents to try and maintain approximately equal temperatures in all rectifiers. In particular, when multiple shelves of rectifiers are stacked vertically in frames, the cooling available to each rectifier may not be the same due to differences in inlet air temperature, resulting in unequal temperatures in the rectifiers. Such a scheme can thus compensate for differences in the ambient conditions for the individual rectifiers, and ensure that the rectifiers are all stressed about the same thermally, thus improving overall reliability.

Recharge Current Limit

In some battery-plant applications, it is desirable to limit the current into the battery following a discharge. This can also be accommodated by a variation of the new architecture. The current variable of interest, e.g. the battery current, can be monitored and each rectifier put into a constant-current mode, so that the battery current is kept below the desired limit. As the battery gets charged, the plant voltage will automatically be adjusted to maintain the battery current. When the battery has been charged at the recharge current limit for a suitable timed period, the control of the plant can revert to a mode such as plant voltage control, and the batteries can be float charged.

V. Features Enabled By Digital Control

The use of digital control to implement some of the functions such as plant voltage regulation and current sharing among rectifiers, that have in the past been performed by analog control, results in much greater flexibility. Since microprocessors were first used in battery plants about two decades ago, the trend has been for more digitalization of control and alarm functions. With the use of microprocessors in the rectifier, and the implementation of a high-speed digital interface between them, many more functions can also be implemented. Some of these are:

- Automatic rectifier identification
- Automated and flexible plant configuration
- Access to many more rectifier variables such as temperature, overvoltage limits, current limits, and the ability to dynamically adjust these limits while the plant is operating.
- The ability to implement sophisticated battery charging techniques such as recharge current limiting, timed boost voltage charging or intermittent charging.
- Being able to assess battery capacity by performing a partial discharge test. The rectifier output voltage is reduced to a level so as to discharge the batteries using the load.
- Remote monitoring and adjustment of plant parameters such as battery float voltage, current limits or overvoltage thresholds.

The use of a serial bus to implement the rectifier-controller interface also has many advantages. The first is that the wiring and connector requirements are dramatically reduced over a parallel bus. By using an appropriate bus protocol, error correction can be built in, this greatly improving the noise immunity and reliability of the plant control.

The most important benefit of a digital control scheme is that features and functions can be continually improved by using the same hardware platform. It also allows customization to meet particular customer and/or country requirements without having to make large hardware changes.

VI. Conclusions And Summary

A new scheme for precise control of battery plant voltage while simultaneously maintaining active current sharing among the rectifiers has been presented. This scheme has several advantages over conventional schemes such as tighter control of battery float current, easier plant commissioning procedures and avoiding adjustment procedures when plant configurations are changes. When implemented using digital control, the overall plant reliability can also be improved. Implementation guidelines have been discussed and variations that support constant-current operation of the plant have also been presented.

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References

[1] C. Gennas, "Future Trends in DC Power Plants", Proceedings of the 1979 International Telecommunications Energy Conference, pp. 1-5.

[2] T. Papathomas, R. Scuderi, "Stored-Program Control of DC Power Plants", Proceedings of the 1981 International Telecommunications Energy Conference, pp. 18-23.

[3] P. Gensinger, E. Rosin, "Microprocessors in Power Control, The Time has Come", Proceedings of the 1981 International Telecommunications Energy Conference, pp. 1-6.

[5] J. C. Brooke, C. A. Lanzone, V. J. Thottuvelil, "Control System for a Modular Power Supply and Method of Operation Thereof", U.S. Patent 5,740,023, 1998.