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TO: XXX/Scientific & Technical Information Division
   Attn: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General
      Counsel for Patent Matters

SUBJECT: Announcement of NASA-Owned U.S. Patents in STAR

In accordance with the procedures agreed upon by Code GP and Code
KSI, the attached NASA-owned U.S. Patent is being forwarded for
abstracting and announcement in NASA STAR.

The following information is provided:

U.S. Patent No. : 3,600,599

Government or Corporate Employee : TRW Inc.
                                        Palmdale, CA.

Supplementary Corporate Source (if applicable) :

NASA Patent Case No. : GSC-10,135

NOTE - If this patent covers an invention made by a corporate employee
of a NASA Contractor, the following is applicable:

YES ☑ NO 

Pursuant to Section 305(a) of the National Aeronautics and Space Act,
the name of the Administrator of NASA appears on the first page of the
patent; however, the name of the actual inventor (author) appears at
the heading of column No. 1 of the Specification, following the words
"...with respect to an invention of ..."

Bonnie L. Henderson

Enclosure (NASA-Case-GSC-10135) SHUNT REGULATION ELECTRIC POWER SYSTEM Patent (NASA) CSCL 09C

N78-17296 Unclas

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SHUNT REGULATION ELECTRIC POWER SYSTEM

ABSTRACT: A regulated electric power system having load and return bus lines. A plurality of solar cells interconnected in power supplying relationship and having a power shunt tap point electrically spaced from the bus lines is provided. A power dissipator is connected to the shunt tap point and provides for a controllable dissipation of excess energy supplied by the solar cells. A dissipation driver is coupled to the power dissipator and controls its conductance and dissipation and is also connected to the solar cells in a power tapping relationship to derive operating power therefrom. An error signal generator provides an error output signal which is representative of the difference between the electric parameters existing at the load bus and the reference signal generator. An error amplifier is coupled to the error signal generator and the dissipation driver to provide the driver with controlling signals.
1. FIELD OF THE INVENTION

This invention relates generally to electric power supply systems and more particularly to electrical regulation thereof vis-à-vis effectively nonconstant source elements and/or varying conditions of energy storage and load utilization.

Although the invention finds particularly advantageous application in the field of multielement arrays of solar cell power supplies coupled to storage batteries for powering equipment and instrumentation remote from conventional power sources such as space satellite applications, and although in the cause of brevity and clarity of presentation much of the following discussion and description of examples of the invention relate particularly thereto, it is expressly to be understood that the advantages of the invention are equally well manifest in other fields of electric energy supply such as, for example, the utilization of thermoelectrics, fuel cells, and the like where load conditions and source output capacity may widely vary as in a cyclic or lifetime degrade manner.

2. DISCLOSURE OF THE PRIOR ART

With particular reference, therefore, to photovoltaic power sources, and their regulation as in large area, multicell solar array-storage battery systems, it has long been recognized that such systems present a particularly severe problem of supply parameter regulation. These systems typically comprise a very large number of very low output photocells which are interconnected in a matrix network to provide predetermined output voltages and current magnitudes constituting a desired useful supply of power. The problems of providing predetermined and usefully regulated output parameters are increased by extreme temperature variation and nonconstant incidence of solar radiation on the individual transducer elements; that is, the angle of incidence and magnitude of intensity of the radiation typically vary over very great ranges due to (1) vehicle orientation causing structure eclipse and (2) orbit location causing terrestrial eclipse. Furthermore, the individual cells have a finite normal lifetime and suffer, on a system basis, a relatively high probability of failure of individual ones of the cells. In addition, the load or utilization parameters typically vary over very great ranges. Finally, all these problems are intensely aggravated by the requirement for maximum system lifetime without possibility, because of the extreme remoteness, of repair, rebuilding, or replacement of any system components.

Prior art approaches to the problems enumerated have typically been directed toward providing series regulator apparatus connected in series between the source panel and its utilization load. The regulation is achieved by blocking and dissipating excess power from the array whereby a predetermined load or bus voltage or current is maintained. The disadvantages of such series dissipative regulators result from the design of the regulator to conduct the full load current which mandates a large dissipative capability particularly, for example, during post eclipse portions of the cycle when the storage batteries are typically demanding maximum charge current and the array, although illuminated, is still cold. In addition, the series arrangement generally requires considerable drive power and causes appreciable loss of array power when no dissipation is required or desired during periods of partial eclipse or at the times approaching system end of life. These difficulties of series regulation can be obviated by complex bypassing and switching circuitry or by adding compensating additional transducer cells to the array. Either solution, however, constitutes a cost disadvantage in adding weight and complexity and adds to system failure probability.

Prior art shunt regulation techniques have heretofore typically been directed toward providing apparatus which achieves dissipation of excess array power in a substantially brute-force manner. Again, unless complex circuitry is utilized, the minimum standby power for control and drive of the shunt dissipator apparatus requires additional source elements in the transducer matrix. Further, the large amounts of maximum power to be dissipated in such systems places a considerable life-shortening stress on the control and dissipative elements and creates significant problems of removing heat from the electrically dissipative elements.

Other attempts in the prior art have been directed toward the utilization of high frequency switching techniques whereby the source power is coupled to the load in a cyclically actuated time gated manner. These techniques, as thus far disclosed in the art, have resulted in complex, less than acceptably reliable, large, massive, and costly structures which, in addition, requires costly and heavy filtering devices and which has proven difficult with which to incorporate redundancy for satisfactory reliability configurations.

Accordingly, it is an object of the present invention to provide a novel electric power regulation system which is not subject to these and other disadvantages and limitations of the prior art.

It is another object to provide such apparatus which does not require that the regulator carry the load current.

It is another object to provide such apparatus which dissipates power substantially only when excess, undesired power is being generated.

It is another object to provide such a system which is relatively simple and electrically rugged with high inherent reliability.

It is another object to provide such apparatus which requires control power of sufficiently small magnitudes as to permit a smaller, lighter, less costly, and more reliable power source.

It is another object to provide such a system which exhibits a very fast and accurate response to regulation needs.

It is another object to provide such apparatus which neither causes ripple in the load power nor requires the incorporation of filtering devices therewith.

It is another object to provide improved shunt regulation apparatus which is capable of controlling large amounts of power while requiring the dissipation of only small fractions thereof and which may thereby greatly reduce the thermal stresses in the dissipation system.

It is another object to provide such a system which for a given load requirement requires a smaller number of photocell transducers and which utilizes, for standby control power, only approximately 1 percent of the end of life capability of the array matrix.

SUMMARY OF THE INVENTION

Very briefly, these and other objects are achieved in a solar cell array example of the invention which includes a shunt regulator dissipation system tapped across a portion only of the array of photocells. A driver circuit which controls the dissipation achieved is supplied similarly from a tap point of the array. An error signal generator receives input signals from the load bus and from a reference and supplies the error signal through appropriate amplification circuitry to the driver.

All of the circuitry after the error signal generator may be biased off whereby there is substantially zero drain from either the load bus or the array unless there is an excess of power, which desirably, is to be dissipated.

The combination of this example includes novel redundancy reliability configurations in the power dissipation components and minor loop feedback stabilization configurations in the low-power control network portions.

Further details of these and other novel features and their principles of operation as well as additional objects and advantages of the invention will become apparent and be best understood from a consideration of the following description when taken in connection with the accompanying drawings which are all presented by way of illustrative example only.
renders a control signal for a driver amplifier 38. The driver 75 decreases the active element thermal stresses.

The output characteristic is displayed in FIG. 2B wherein \( I_{\text{out}} \) is plotted as a function of the array voltage. Assuming a desired load current \( I_{\text{L}} \), and a desired load voltage \( V_{\text{L}} \), and the array being operated at the point on the array characteristic curve 52, it may be seen that the difference \( I_{\text{L}} - I_{\text{out}} \) is the current to be shunted thereby to dissipate the power \( I_{\text{out}} \) which is shown by the shaded area on the graph and must be dissipated by the transistor 46. The power to be delivered to the load is the larger, unshaded, rectangular area below the shaded rectangle.

In FIG. 3A a portion of an example of the high efficiency shunt regulator of the present invention is illustrated and includes a series string of photovoltaic transducers 54, 56 connected between a load bus 58 and a return bus 60. The dissipative shunt circuit is shown connected between a shunt power tap point 62 and the return bus. The shunt circuit comprises a passive dissipative portion indicated by the resistor 64 and a power transistor 66. The total array voltage is \( V_a \) and is the sum of the tap-to-bus voltages \( V_{i}, V_{j} \) load bus current and \( I_{\text{L}} \) the effective shunt loop current.

Referring to FIG. 3B, the total or overall array characteristic is shown resolved into two component characteristics each related to a respective set \( V_{i}, V_{j} \), as illustrated by the curves 68, 70 respectively. (It should be noted that the curves 52, 68, and 70 are drawn to approximately the same scale).

Assuming again that \( I_{\text{L}} \) is the desired output current and \( V_{\text{L}} \) is the desired output voltage, the upper element 54 may be operated at the point 72 on the curve 70 thus providing a voltage \( V_{i} \). The element 56 in order to operate at the desired voltage \( V_{j} \) is then controlled to operate at the point 74 on the characteristic 68. Operation at the point 74, however, is seen to require shunting of the current \( I_{\text{L}} \), being again the difference between \( I_{\text{L}} \) and \( I_{\text{out}} \) as they relate to the curve 68. The consequent dissipation, however, is only of the power represented by the area \( I_{\text{L}}V_{\text{L}} \) on the curve 68. In this particular illustration, the power to be dissipated is due to the composite characteristic of the elements 54, 56, and is of the order of half that for the prior art full shunt case. The dissipation in the amplifier element 66 is further reduced by the passive dissipator resistor 64. Thusly the current and thermal stresses on the dissipative components is greatly reduced resulting in their increased lifetimes and permitting the design deletion of much thermal energy transfer apparatus for removing heat from the dissipative elements.

In FIG. 4 an array 76 of photovoltaic transducer elements is illustrated in which a number of electrically similar shunt tap power points 78, 80 are shown to each of which is connected a controlled dissipative shunt element 82, 84, respectively. In FIG. 5, the tap points 78', 80' are shown electrically connected with the dissipative elements 82', 84' connected directly in parallel. Again passive dissipative elements may be incorporated to increase further the system reliability and decrease the active element thermal stresses.
Referring to FIG. 6, a further example of increased dissipation
capacity and reliability is illustrated. An array 86 is shown
having a power shunt tap at the point 88 to which is coupled
a series quad amplifier arrangement 90 of power transistors 92,
94, 96, 98. The quad configuration is common-base driven
from a driver current control circuit 100 controlled in turn by
a signal from the error amplifier, not shown, and deriving
its operating power from the array at the reduced voltage (with
respect to the load bus voltage) point 102. During normal
mode operation, the dissipation of the energy associated with
\( I_{\text{sh}} \) drawn from the tap 88, is equally shared by the two quad-
amplifier transistors 92, 96. When, however, any one of the
transistors fails in either open or shorted mode, the amplifier
continues to operate.

The example of FIG. 6 further illustrates the reduced
minimum power drain and dissipation of the driver circuit
from the source array 86. Assuming that a given driver current
\( I_d \), required at the base bus 104, the power dissipated by the
driver 100 is, to at least a good approximation, the product
\( I_d V_d \) where \( V_d \) is the voltage across the driver circuit as
indicated. Conventionally \( I_d \) is drawn from the load bus thusly
maximizing the efficiency as shown by the load bus. In accordance with
the present invention the power for the driver being taken
from a reduced voltage point 102 significantly reduces the
maximum power drain caused by the driver apparatus.

An example of the error amplifier stability and reliability
configuration of the invention is illustrated in FIG. 7. The
error amplifier is seen to include three stages 106, 108, 110
coupled in a cascade relation between the error signal gener-
ator 32 and the driver network 38. When it is assumed that the
functions \( A_1, A_2, A_3 \) of each stage could vary by, say, a factor of 2,
then the overall amplifier variation could be a factor of 8. The
minor loop feedback combination indicated, which includes a
respective feedback proportion \( H_1, H_2, H_3 \) gain \( A_1A_2A_3 \)
where \( A_1 = (1/A_1H_1) \) and can be well approximated as \( A_1 \\
= 1/H_1 \), when \( A_1H_1 > 1 \). Accordingly the total gain variation can be
realistically very small since the total gain \( > 1 \)
\((H_1H_2H_3)\) and each of the feedback loops may consist of
passive, drift free components.

Current amplifier stages may, as desired, similarly combine
gain stabilization as shown in the illustration of FIG. 8. The
current gain of the typical stage 112 is stabilized by combina-
tion of selected base and emitter resistors. The stabilizing
selection may be made in a manner to satisfy the relation
\( I_b \approx R_b R_h \) wherein \( I_b \) and \( I_h \) are collector and base current
magnitudes, respectively, and \( R_b \) and \( R_h \) are the ohmic values
of the base and emitter resistors, respectively.

Referring to FIG. 9 as Majority Voting AND Gate example
of the 1x4 illustrated as a combination with three redundant
amplifiers 112, 114, 116 each intrinsically stabilized as indi-
cated and each fed by a separate, redundant error signal genera-
tor 120, 122, 124 and associated reference. Where the
output signal of each error amplifier is \( V_{1}, V_{2}, V_{3} \) respectively,
they are coupled to the six element Majority Voting AND
Gate amplifier as shown to provide the output error signal, to
the driver. \( V_D = (V_1 + V_2 + V_3) - (V_1 + V_2 - V_3) \) wherein the
dot operator and the plus operator is defined as "or." Accordingly, it is clear by inspection that \( V_D \) is highly
stable with respect to the "error" associated with the load bus
irrespective of any failures in a reference, amplifier, feedback,
or gate element.

There have thus been disclosed and described a number of
examples and novel structural aspects of an electric power
regulation system which achieves the objects and exhibits the
advantages set forth above.

We claim:

1. A regulated electric power system comprising:

a plurality of electric energy generator elements connected
between said load and return bus means in a power supply-
ing relation; and being interconnected in a manner providing at least one power shunt tap point electrically spaced from each of said bus means, said plurality of electric energy generator elements being a matrix array of photovoltaic cells and said shunt tap point is electrically disposed within said array;

2. A regulated electric power system comprising:

a plurality of electric energy generator elements connected between said load and return bus means in a power supply relation thereto and being interconnected in a manner providing at least one power shunt tap point electrically spaced from each of said bus means, said plurality of electric energy generator elements being a matrix array of photovoltaic cells and said shunt tap point is electrically disposed within said array;

3. A regulated electric power system comprising:

a plurality of electric energy generator elements connected between said load and return bus means in a power supply relation thereto and being interconnected in a manner providing at least one power shunt tap point electrically spaced from each of said bus means, said plurality of electric energy generator elements being a matrix array of photovoltaic cells and said shunt tap point is electrically disposed within said array;

4. A regulated electric power system comprising:

a plurality of electric energy generator elements connected between said load and return bus means in a power supply relation thereto and being interconnected in a manner providing at least one power shunt tap point electrically spaced from each of said bus means, said plurality of electric energy generator elements being a matrix array of photovoltaic cells and said shunt tap point is electrically disposed within said array;