VR31 Auxiliary Generator Regulator

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AUXILIARY GENERATOR REGULATOR WITH 3-STAGE BATTERY CHARGING

INTRODUCTION

Enerpro's VR31 Auxiliary Generator Voltage and Current Regulator Module with Three-Stage Charging, shown in Figure 1, is a direct plug-in replacement for the VR10 - VR16 auxiliary generator voltage regulator modules used in EMD locomotives. In conjunction with an external current sensor, the VR31 provides three-stage battery charging for longer battery life, faster charging, reduced water consumption in flooded lead acid (FLA) batteries, and compatibility with valve regulated lead-acid (VRLA) and lithium-ion batteries. A novel solid-state circuit replaces a problematic bootstrap contactor to power-up the generator from residual magnetism. The VR31 is compatible with both ac and dc auxiliary generators.

Figure 1 – VR31 Auxiliary Generator Voltage and Current Regulator Module

APPLICABLE DOCUMENTS

- Block Diagram E1754, VR31 Aux Gen Regulator with Three-Stage Charge Profile
- Mechanical Diagram M2101, VR31 Assembly
- Mechanical Diagram M2106, EBCS-3 Battery Current Sensor
- Schematic Diagram E1742, AG3SCR 3-Stage AG Charge Regulator Board
- Schematic Diagram E1833, VR31 Test Point Board
- Schematic Diagram E1809, Hall Sensor Power Input Board

ONE-STAGE CHARGING WITH VR10 – VR16 REGULATOR CARDS

Operators report that locomotives that are shut down and restarted multiple times per day due to fuel cost or pollution regulations experience a premature loss of battery capacity. This problem is caused by the one-stage charge profile provided by the conventional locomotive auxiliary dc power system.

With one-stage charging, as shown in the voltage and current vs. time profile in Figure 2, the auxiliary generator voltage is regulated to a constant 74 Vdc (typical). Charging current is limited by the cable resistance of about 20 mΩ between the generator and battery augmented by a 50 mΩ resistor, bringing the total resistance to about 70 mΩ. With the generator at a constant 74 V, the battery terminal voltage at 125 A is about 74 V – 125 A * 0.07Ω = 66 V. As charge proceeds, the charging current decreases and the battery voltage increases. After several hours of operation with the engine running, the current may have fallen to 30 A which results in a battery voltage of 74 V – 30 A * 0.07 Ω = 72 V. If the engine is shut down at this time, the final charging voltage will be 6 V less than the 78 V (2.44 Volts per cell) required for a complete recharge.

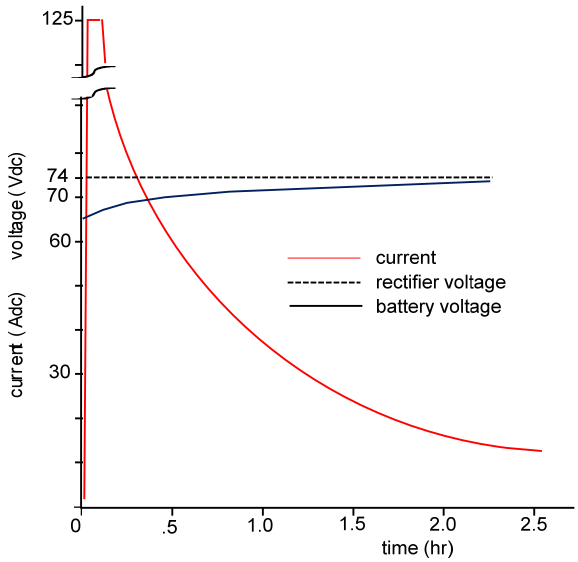


Figure 2 – One-Stage Charge Profile

Battery manufacturers recommend applying 2.44 Volts per cell, or 78 Vdc for a 32 cell battery, during recharge for a time sufficient to remove the amorphous lead sulfate ($PbSO_4$) that accumulated on the plates during the previous discharge. If the lead sulfate is not completely removed before charging is terminated by engine shut down, the sulfate coating on the plates thickens and crystallizes, becoming less conductive with each charge-discharge cycle. The result is that the battery progressively loses its ability to accept charge – a process called sulfation.

The VR10 – VR16 series of auxiliary generator voltage regulators uses a normally-closed contactor in parallel with the pulse width modulator (PWM) power transistor to temporarily connect the output of the auxiliary generator directly to its field winding. The generator's residual magnetism provides enough magnetic flux to produce several volts of rectified stator ac voltage (or armature dc voltage if the generator is a dc machine). With the normally closed bootstrap contactor connecting the stator to the field, the residual stator voltage starts the bootstrap process. An increase in stator voltage causes an increase in field current which causes an increase in stator voltage, ad infinitum. The coil of the bootstrap contactor is energized and the contacts open when the stator voltage reaches a substantial fraction of 74 V.

At this time, the power transistor, now inserted between the stator and the field, operates at variable duty cycle to maintain the field current necessary to hold the stator voltage at 74 V as the generator speed, battery current demand and external load current demand change during normal locomotive operation.

The bootstrap contactor has been a problematic component of the VR10 – VR16 series of regulator cards because of the highly inductive load and the presence of a rapid switching transistor in parallel with the contacts. If the normally closed contacts fail to open after the bootstrap circuit has built up the generator voltage, due either to welded contacts or a fault in the coil or coil drive circuit, the resulting uncontrolled generator field current will increase the generator voltage to a level that causes the over-voltage protection circuit to trip the circuit breaker.

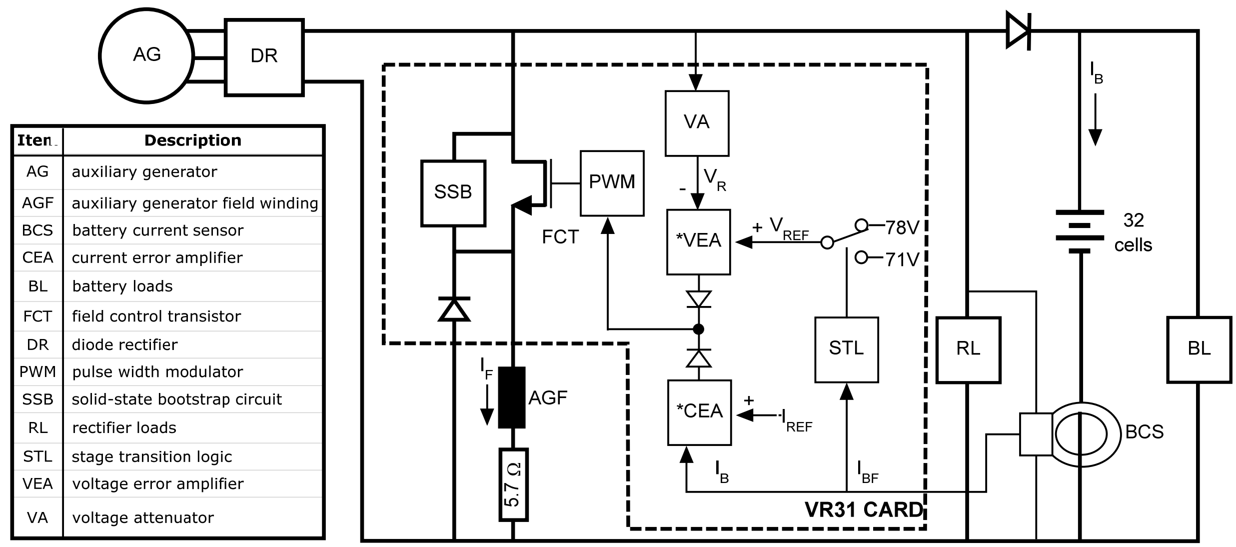
THREE-STAGE CHARGING WITH THE VR31 REGULATOR CARD

Block Diagram

The block diagram of the auxiliary dc power system is shown in Figure 3. The VR31 module plugs into an EMD-2 type card cage. It is composed of four major components:

- Front panel circuit breaker
- AG3SCR control board
- Front panel LEDs and test points
- Rear panel contact pins that plug into mating sockets in the rear of the card cage

A galvanically isolated Hall effect battery current sensor (Enerpro part number EBCS-3) is installed on the battery cable near the knife switch.



Item	Description
AG	auxiliary generator
AGF	auxiliary generator field winding
BCS	battery current sensor
CEA	current error amplifier
BL	battery loads
FCT	field control transistor
DR	diode rectifier
PWM	pulse width modulator
SSB	solid-state bootstrap circuit
RL	rectifier loads
STL	stage transition logic
VEA	voltage error amplifier
VA	voltage attenuator

Figure 3 – Auxiliary Power System Block Diagram

THREE-STAGE CHARGE PROFILE

As shown in Figure 4, the three-stage charge profile produced by the VR31 regulates the first, or bulk stage, current to about 20% of the battery's capacity per manufacturers' recommendations. In the second, or absorption stage, the rectifier voltage is regulated to 78 V. This elevated voltage converts the maximum amount of active battery material while equalizing the charge in each cell, thus minimizing sulfation and capacity loss. In the third, or float stage, the VR31 maintains voltage regulation but at a lower setpoint (72 V). In this mode, the battery draws only a little more than the self-discharge current required to maintain full charge.

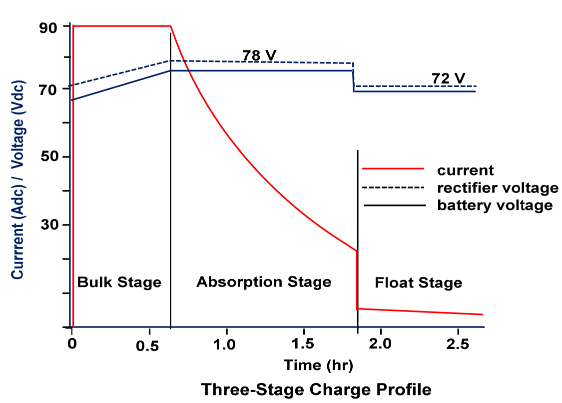


Figure 4 – Three-Stage Charge Profile

The result is negligible loss of electrolyte in the float stage. This benefit is especially important with Valve Regulated Lead Acid (VRLA) batteries.

Bulk Stage

Upon engine start, the VR31 commands a bulk stage current of 90 amps. The battery behaves as a capacitor in that the constant charging current results in battery voltage increasing with time. The bulk stage ends when the voltage reaches the 78 V limit. When charging from a low initial state of charge, approximately 80% of capacity is stored in the bulk stage. The characteristic response of the voltage and current regulators provide the transition between the bulk and absorption stages.

Absorption Stage

With voltage fixed at 78 V, the battery current in the second stage decays approximately exponentially with time from the initial bulk stage current until one of two absorption stage termination criteria are met. These criteria are:

- either the steady-state absorption stage current falls to typically 25 A, or
- the second derivative of battery charge, d^2Q/dt^2, falls below a preset threshold.

Typically, 95% of battery capacity is stored if the engine runs long enough for the charge process to reach the end of the absorption stage.

Forcing the absorption-to-float transition to occur as a function of the second derivative of charge (a patent-pending methodology) provides a form of inherent temperature compensation. Current in this stage decreases less rapidly with increased battery temperature. As a result, higher temperature causes the charge limit to be reached in shorter time. This is what would happen if the absorption stage voltage were to be decreased with increasing temperature. Transitioning from the absorption to the float stage as a function of the second derivative of charge also assures that a shorted cell or other battery defect will not result in continuous operation at elevated voltage.

A comparator monitors the battery current feedback signal and forces the float transition when the current is less than 25 A. A voltage-to-frequency converter and microcontroller perform the d^2Q/dt^2 computation.

For VRLA batteries the absorption stage voltage is reduced to 76 V per manufacturers' typical recommendations.

Float Stage
The voltage regulator holds the rectifier voltage at 72 V (2.22 Vpc) as a result of a change in the voltage command from 78 V to 72 V when one of the two absorption/float transition criteria is met. This allows the battery to draw the required self-discharge current. This voltage is maintained until engine stops. Electrolyte loss is negligible in the float stage.

VR31 Functional Description

Front Panel Circuit Breaker
The circuit breaker over-current trip level is 30 A. The breaker trip delay is the minimum delay available from the breaker manufacturer. The resistance of the generator field winding and its external series resistance is about 10 Ω. Thus, a short circuit between the generator voltage input to the AG3SCR board and the connection to the field winding will occur if the generator voltage reaches 10 Ω * 30 A = 300 V.

The circuit breaker contains a shunt trip winding that is tripped by a signal from the AG3SCR board before the generator voltage reaches a damaging level.

An improved circuit breaker is used that may be manually reset upon overvoltage trip, but is designed to prevent manual trip.

AG3SCR Control Board
The control board contains the following circuits:

- self-excitation
- low voltage power supply
- voltage and current regulation
- shorted PWM transistor protection
- loss of feedback protection
- diagnostics

Self-Excitation
In the bootstrap circuit of the AG3SCR board, the PWM transistor is bypassed by a normally on bootstrap transistor instead of the problematic NC contactor of the VR10 – VR16 series of regulator cards.

Immediately after engine start, a control transistor turns on the bootstrap transistor in response to the initial generator voltage produced by the generator's residual magnetism. The generator then self-excites from field current passing through the bootstrap transistor. When the generator voltage reaches about 30 V, the control transistor turns off the bootstrap transistor and the PWM transistor takes over control of the field current. The current and voltage regulator circuits then act to control the duty cycle of the PWM transistor to adjust the generator field current (about 10 A maximum) to obtain the generator voltage and current required for the 3-stage battery charge while supplying current to the varying loads (HVAC, lighting, etc.). The AG3SCR board also contains the essential circuitry that protects the connected loads from over-voltage.

Low voltage Power Supply
The low voltage power supply provides +12 V and +5 V control power and reference voltages. A Zener pre-regulator is sourced from the generator voltage to provide a limited voltage input to the 12 V and 5 V precision regulators. The pre-regulator incorporates a positive temperature coefficient input resistor that allows the precision regulators to come into regulation during the bootstrap phase while avoiding high pre-regulator dissipation at the normal generator operating voltage.

Voltage and Current Regulation
Separate voltage and current control loops provide regulation. Current is limited to the commanded value when charging current exceeds the current setpoint. Similarly, voltage is limited when the generator voltage exceeds the voltage setpoint. The absorption stage voltage command is adjusted by a board-mounted potentiometer. Voltage is limited to the absorption level of 78 V after the bulk stage

current reaches the current setpoint. After the absorption/float stage transition, the voltage command is reduced to produce the 72 V float voltage.

Shorted PWM Transistor Protection

At high engine speed, the auxiliary generator will produce dangerously high voltage if the PWM transistor or the bootstrap transistor becomes shorted or if either transistor is turned on continuously due to a component failure. In this event, an over-voltage comparator trips the panel-mounted circuit breaker if the auxiliary generator voltage exceeds the over-voltage trip threshold. This threshold is provisionally set at 115 V.

Loss of Voltage Feedback Protection

The generator voltage feedback signal is derived from the same rear panel conductor as the AG3SCR circuit board power. An open circuit in this conductor removes power from the board thus causing the generator voltage to revert to the low residual voltage.

Loss of Current Feedback Protection

An open circuit signal or loss of power to the current sensor causes the current signal input to the AG3SCR board to default to a higher than normal level. A circuit on the AG3SCR board senses this condition and forces the regulator into the 72 V float mode while indicating a current sensor fault on the front panel.

COMPUTER INTERFACE

Enable/Inhibit

No computer interface is required to enable the VR31 board. As described above, the VR31 bootstraps the generator and commences the bulk stage charge immediately after the engine starts. The VR31 shuts down and resets each time the engine is turned off.

FRONT PANEL LEDS AND TEST POINTS

Tables 1 and 2 provide a description of the VR31 LEDs and test points. Note that all test point signals are connected through attenuators or current limiting resistors.

LED	Color	Description
Charge Stage 1, 90 A	Blue	Bulk stage, VR31 in current regulation
Charge Stage 2, 78 V*	Yellow	Absorption stage, VR31 in voltage regulation
Charge Stage 3, 72 V	Green	Float stage, VR31 in voltage regulation
Current Sensor Fault	Red	Indicates loss of current feedback

Table 1 -- Front Panel LEDs

*Note: Absorption voltage is 76 V for VRLA configured VR31 modules.

Test Point	Color	Description
RP	Orange	Rectifier positive voltage
BP	Red	Battery positive voltage
AC1-AC3	Yellow	Generator ac line voltages
FLD	Blue	Field voltage
IB+	Red	Current sensor voltage, scaled to 1 V = 100 A
IB-	Black	Current sensor signal common, circuit common, BN

Table 2 -- Front Panel Test Points

LOCOMOTIVE CONNECTIONS

All connections to the locomotive system are made using the pin and socket card-edge interface to the card cage installed on the locomotive. The standard fast-on terminal block on the rear edge of the card cage facilitates connection to the appropriate components. Table 3 describes the connections.

Pin	Signal	Description
1, 2	BCP	Auxiliary generator rectifier output
3	CSS	Current sensor feedback signal
4	AC1	Auxiliary generator ac mains phase 1
5, 8	FLD	Auxiliary generator field voltage
6	AC2	Auxiliary generator ac mains phase 2
7	BATT	Positive battery terminal, feed-through to optional data recorder only
9	CSP	Current sensor positive supply, connected to BCP through 2A fuse
10	AC3	Auxiliary generator ac mains phase 3
11	LOAC	Low ac voltage fault signal, NO relay contacts with 5.0 kΩ resistor to BN
12	CSF	Current sensor fault signal, NO relay contacts with 5.0 kΩ resistor to BN
13	CSR	Current sensor return, direct feed-through to BN
14	BN	Negative battery terminal and circuit common

Table 3 -- VR31 Rear Panel Connections

Document Revision History			
Revision	**Date**	**Notes**	**Approval**
NC	03/2011	Initial Release	fjb
A	08/2011	Updated operational features for AG3SCR Revision F	jtm
B	10/2013	Correct Figure 3, add VRLA information	Jtm
C	08/20/16	Correct Enerpro address to new location	dli