PROPER OPERATION OF STEP VOLTAGE REGULATORS IN THE PRESENCE OF EMBEDDED GENERATION

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INTRODUCTION

Increasing levels of embedded (dispersed) generation pose new challenges to utilities. Traditionally, distribution networks have been used purely to transport energy from the transmission system down to lower voltage levels. A generator delivering electricity directly to the distribution network reverses the normal power flow direction. Conventional "reverse power flow" detection schemes may operate incorrectly, resulting in unacceptable system conditions. New functionality in a programmable electronic control unit for step voltage regulators properly discerns when reverse power flow is a result of embedded generation rather than system switching. This capability allows the utility to accurately monitor and control system voltage levels in the presence of embedded generation.

SUMMARY

The Electricity Supply Board (ESB) of the Republic of Ireland has been using step voltage regulators with programmable electronic controls on their medium voltage (MV) distribution lines for many years. With the introduction of embedded generation, the company was faced with a new challenge.

Generators connected to ESB's MV network supply real power *to*, whilst absorbing reactive power *from*, the system. When an embedded generator exports power the power flow on the network is in the opposite direction to normal. In this case, conventional "reverse power flow" detection schemes may incorrectly trigger a reversal of step voltage regulator operation, resulting in unacceptable voltage levels. Commercially available power-flow detection techniques were unable to distinguish between the power flow reversal caused by the generator power export and that caused by system switching.

The work described in this paper determined a way of detecting when reverse power flow was a result of embedded generation rather than system switching. This new capability allows the programmable electronic control to differentiate between these two conditions. Operation of this advanced capability has been tested and verified using an analog real-time distribution system simulator, and successfully field-tested by ESB. Results have shown that even in the presence of embedded generation power flows can be accurately monitored and voltage levels correctly controlled. Consequently a barrier to the connection of generators to ESB's distribution network has been removed.

VOLTAGE REGULATOR BASICS

A step voltage regulator (SVR) controls line voltage levels to ensure that the voltage received at the customer's premises remains within statutory limits. An SVR is an autotransformer in which the series winding is tapped and equipped with a reversing switch that permits its voltage to add or subtract from the shunt winding voltage. This permits the voltage regulator to increase (boost), or decrease (buck), the voltage on the load side relative to the source side voltage level. A winding senses the load side voltage and supplies this intelligence to a control which in turn activates an automatic tap changer on the series winding to raise or lower voltage.

SVRs are usually designed to regulate voltage in the range +/-10%, in 32 steps, with 5/8 percent voltage change per step. Figure 1 demonstrates the basic schematic for a typical step voltage regulator.
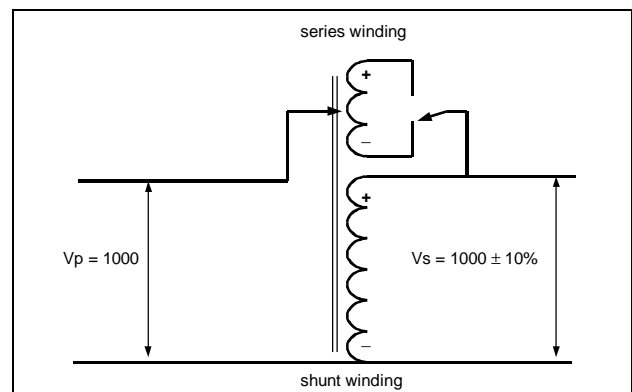

Figure 1. Basic Schematic of a Single-Phase Step Voltage Regulator

Single-phase SVRs may be applied to a distribution system in a variety of configurations as listed below.

- A single-phase circuit

- One phase of a three-phase wye or delta circuit

- A three-phase, three-wire wye or delta circuit with two regulators (open delta)

- A three-phase, four-wire, multi-grounded wye circuit with three regulators

- A three-phase, three-wire wye or delta circuit with three regulators (closed delta)

Three wye connected regulators in a three-phase, four-wire, multi-grounded wye circuit operate independently of each other and the phase angles between voltages and currents remain the same. Open or closed delta-connected units are interrelated. This means that by regulating one phase there is also a voltage change on the other phases. In the case of the open delta configuration, by regulating two phases by +/-10% with regulators, the third phase is also regulated by +/-10%.

With the closed delta configuration, a voltage rise of 10% caused by a regulator operating in one phase also causes a 5% voltage rise in the adjacent phase. This interrelation results in an overall effect of providing +/-15% voltage regulation with the closed delta arrangement.

THE PROBLEM

Intelligent controls for SVRs provide many features and capabilities. Typical controls incorporate digital logic and microprocessor technology. Available control functionality includes voltage limiting, metering, event recording, and reverse power flow detection.

Reverse power flow detection enables the regulator control to recognize situations where system power flow is opposite from the usual direction. This reversal of power flow may be the result of switching operations that reconfigure the feeder, or it may be due to dispersed generation supplying power to the system.

With normal reverse power flow, or bi-directional, sensing, an SVR control determines its direction of operation (forward or reverse) based on the direction of real, or active, power flow.

For a generator to supply real power to the system it must raise its terminal voltage above that of the system. In Figure 2 the Generator's real power export is *less* than the customer demand (kWs) downstream of the SVR. The real power flow through the regulator bank is from *left to right* (Substation to Generator). With normal bi-directional sensing the regulator will be in Forward Mode, regulating the voltage at position (2).
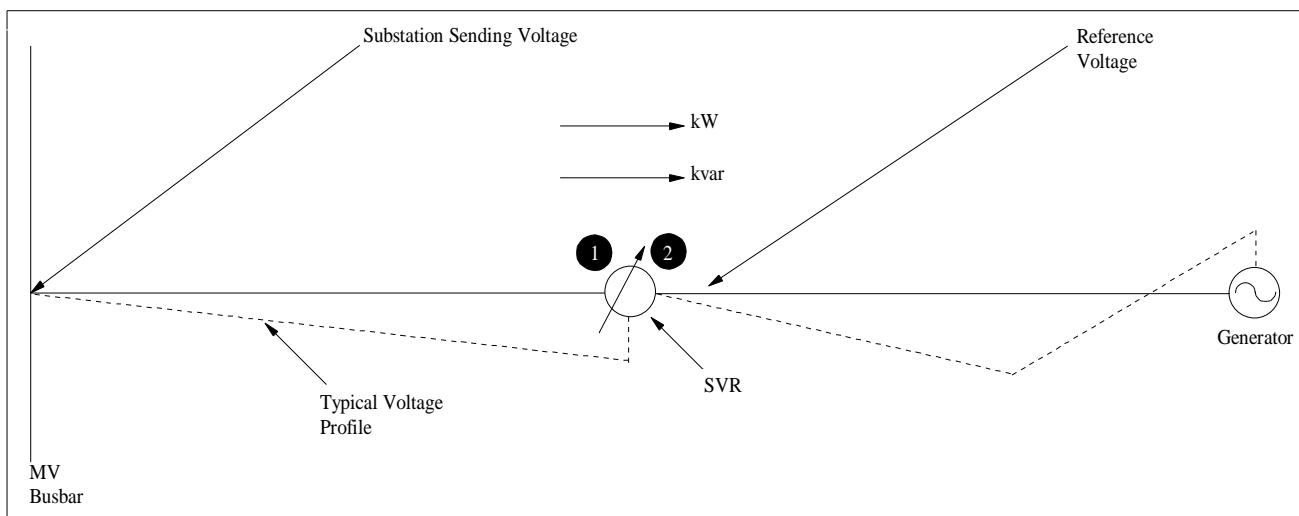

Figure 2. Schematic of Distribution Feeder with Voltage Regulator Bank and Embedded Generator; Real Power Flow from Left to Right
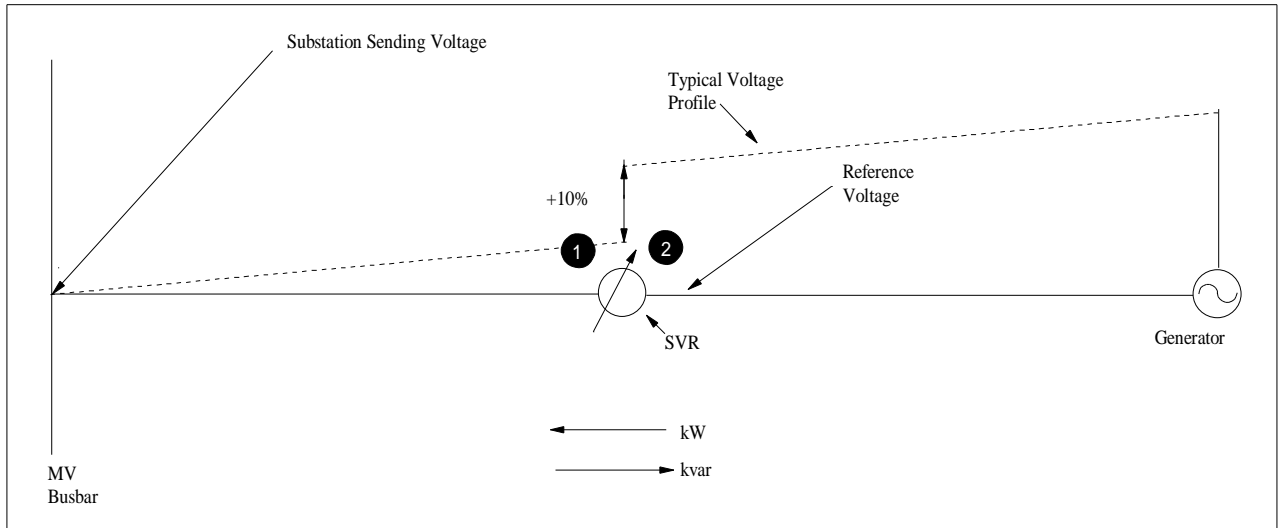(demand customers connected along full length of feeder)

Figure 3. Schematic of Distribution Feeder with Voltage Regulator
Bank and Embedded Generator; Real Power Flow from Right to Left
(demand customers connected along full length of feeder)

In Figure 3, where the Generator export *exceeds* the kW customer demand between the SVR and the Generator, the real power flow through the regulator bank is from *right to left* (Generator to Substation). With normal bi-directional sensing, the regulator would therefore reverse its direction of operation and attempt to regulate the voltage on its source side, position (1). The Substation voltage is effectively fixed and cannot be altered by the regulator bank. If the source side voltage is greater than the set-point voltage for the regulator control, the regulator will tap down in an attempt to lower the position (1) voltage. Since this voltage is fixed by the substation, the net effect is to raise the voltage at position (2). This sequence will continue until the regulator taps to minimum tap, resulting in a 10% (or greater) overvoltage on the Generator side of the regulator bank.

ESB was faced with this situation. When embedded generators supplied power through the SVR towards the substation the standard regulator control sensed a reverse power condition, and reversed its mode of operation. This meant that generators could not be permitted to connect to local distribution lines where existing SVRs might be backfed by more than 50 kW. In many cases this restriction greatly increased connection costs, resulting in ESB's desire to find an economic solution.

THE SOLUTION

While generators connected to ESB's distribution network supply real power to the system, they operate with a leading power factor, that is, they import reactive power from the system. Bearing this in mind an SVR control that determines its direction based on reactive power flows would overcome the problem facing ESB.

A microprocessor-based SVR control was modified to include reactive power flow detection. A new operational mode, Reactive Bi-Directional Sensing, was added. Several of these new controls were manufactured and analyzed in a series of laboratory tests. New controls were also installed in the field on ESB feeders containing embedded generation.

Figure 4 illustrates the operating areas for the new control mode. The new control mode determines the power flow direction by sensing the real and reactive components of the current.

NOTE: The axes in Figure 4 represent real and reactive current magnitudes sensed by the SVR control, not kW and kvar power flows.
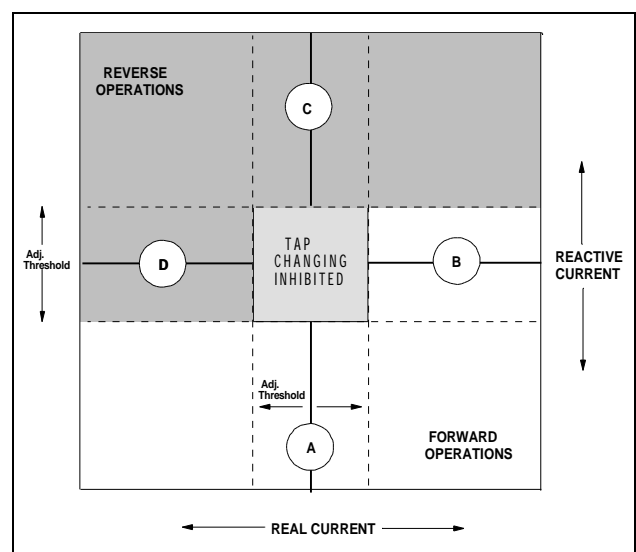

Figure 4. Reactive Bi-Directional Mode Operation

The control incorporates user-definable threshold levels, such that real and reactive current magnitudes greater than the threshold value, positive or negative, trigger specific control-initiated tap changer operations. These adjustable thresholds are illustrated in Figure 4 by the dotted lines flanking the real and reactive axes. Currents with both real and reactive magnitudes less than the threshold levels are illustrated in the figure by the center area labeled "Tap Changing Inhibited".

The control operates in the forward direction whenever the magnitude of the reactive component of the current exceeds the threshold in the negative direction. This corresponds to a reactive power flow (V x I*) from source to load through the regulator. Note that the direction of real power flow does not impact the control's direction of operation. This area of operation is denoted as section "A" in Figure 4.

The control also operates in the forward direction if the magnitude of the real component of the current exceeds the threshold in the positive direction while the magnitude of the reactive component of the current is between the thresholds. In this instance, the real power flow is from source to load through the regulator, and the reactive power flow is small enough such that a source-to-load flow is assumed. This area of operation is denoted as section "B" in Figure 4.

The control operates in the reverse direction using the reverse settings whenever the magnitude of the reactive component of the current exceeds the threshold in the positive direction. This corresponds to a reactive power flow (V x I*) from load to source through the regulator. Note again that the direction of real power flow does not impact the control's direction of operation. This area of operation is denoted as section "C" in Figure 4.

The control also operates in the reverse direction if the magnitude of the real component of the current exceeds the threshold in the negative direction while the magnitude of the reactive component of the current is between the thresholds. In this instance, the real power flow is from load to source through the regulator, and the reactive power flow is small enough such that a load-to-source flow is assumed. This area of operation is denoted as section "D" in Figure 4.

ANALOG SIMULATOR TESTS

The laboratory analysis was performed on a Real-Time Power System Simulator (RTPSS). The RTPSS used here was originally designed and built as a transient network analyzer for Cooper Power Systems' Systems Engineering Group. It has been commercially available since 1974, and is located at Cooper Power Systems' Thomas A. Edison Technical Center in Franksville, Wisconsin, USA. For nearly 20 years, the RTPSS has been internationally recognized as a leading tool for power system studies. It is continually being improved as new technologies are developed.

The RTPSS is a real-time analog device consisting of actual resistance/reactance line models, physical transformer models, etc. Operating at approximately 20 volts RMS, the RTPSS accurately simulates real-life system performance. Faults can be applied, switching operations can be performed, and the system response captured in real time.

For this investigation, a simple power system was modeled as shown in Figure 5. A utility source (S1) and a remote generation unit (S2) are connected to feed a section of distribution feeder that includes two main loads and a step voltage regulator bank in the middle.

Each load models 5MVA at 0.7 reactive power factor. The direction of power flow through the regulator can be controlled by changing the magnitude of the loads or by switching in and out the two sources at different angles. In all cases the convention for positive power flow for the regulator is from S to L. Data shown in the tables is for the following configurations:

I. S_1 closed, S_2 open. Real and reactive power positive.

II. S_1 open, S_2 closed. Real and reactive power negative.

III. S_1 and S_2 closed. S_2 at +30°. Real power negative, reactive power positive.

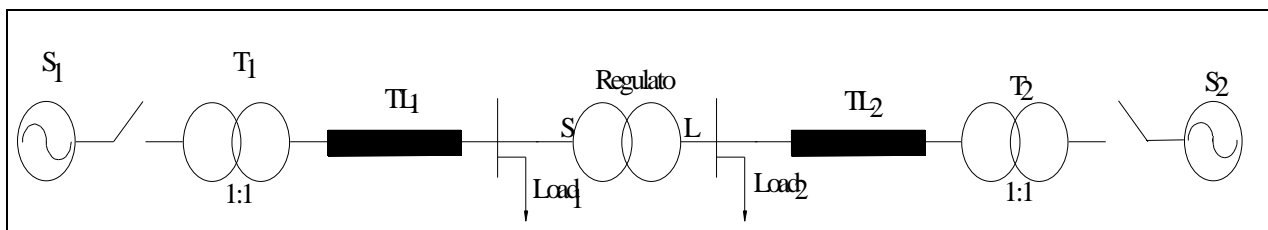IV. S_1 and S_2 closed. S_2 at -30°. Real power positive, reactive power negative.

Figure 5. Real-Time Power System Simulator System Model

Case 1. Four-wire grounded-wye system

The first test case modeled a 4-wire distribution system with a grounded-wye regulator bank configuration. Transformers T_1 and T_2 were connected wye-grounded–wye-grounded. The load models were also wye-grounded. The results are shown in Table 1. In all situations, the regulator responded as expected.

Table 1. Laboratory Test Results for Grounded-Wye Regulator Bank

	Regulator on phases	Operation Mode	P (kW)	Q (kvar)
I	A	Fwd	1013	665
	B	Fwd	915	854
	C	Fwd	919	882
II	A	Rev	-1258	-822
	B	Rev	-975	-926
	C	Rev	-1013	-991
III	A	Fwd	-2550	1337
	B	Fwd	-2591	1169
	C	Fwd	-2935	1149
IV	A	Rev	1903	-2178
	B	Rev	2638	-1676
	C	Rev	2539	-1629

Case 2. Three-wire delta system

Case 2 simulated a 3-wire uni-grounded system with a closed-delta regulator bank configuration. Transformers T_1 and T_2 were connected wye-grounded–delta. The loads were modeled as delta connected. Again, the SVR controls responded as expected, as demonstrated in Table 2.

Table 2. Laboratory Test Results for Closed-Delta Regulator Bank

	Regulator on phases	Operation Mode	P (kW)	Q (kvar)
I	A –B	Forward	1491	1086
	B – C	Forward	1250	1242
	C – A	Forward	1417	1343
II	A –B	Reverse	-1574	-250
	B – C	Reverse	-1380	-473
	C – A	Reverse	-1471	-515
III	A -B	Forward	-1855	1336
	B - C	Forward	-1708	1085
	C - A	Forward	-1732	1485
IV	A -B	Reverse	1572	-717
	B - C	Reverse	1697	-510
	C - A	Reverse	1857	-389

Case 3. Open delta system

For the final laboratory test, a 3-wire uni-grounded system was modeled with an open-delta regulator bank. Transformers T_1 and T_2 were connected wye-grounded–delta. The loads were also delta connected. As Table 3 shows, the regulator control again performed as expected.

Table 3. Laboratory Test Results for Open-Delta Regulator Bank

	Regulator on phases	Operation Mode	P (kW)	Q (kvar)
I	A -B	Forward	1324	897
	C - B	Forward	1150	1185
II	A -B	Reverse	-1378	-176
	C - B	Reverse	-1228	-440
III	A -B	Forward	-1695	1531
	C - B	Forward	-1829	1258
IV	A -B	Reverse	1558	-774
	C - B	Reverse	1816	-320

FIELD TESTING AT ESB–IRELAND

Field Test One

A 10 kV network was identified as a suitable test location. A 500 kVA mobile generator was used to model a typical embedded generator on the ESB system. The modified SVR control was fitted to the existing SVR. The operation of the mobile generator was set such that it was importing reactive power from the system, and its real power (kW) output was increased to a level greater than the kW load downstream of the regulator. The SVR correctly remained in the forward mode of operation, regulating the load-side voltage.

Field Test Two

For the same feeder configuration, the operation of the mobile generator was set such that it was exporting reactive power (kvar) to the system, that is, its kvar output exceeded the kvar load demand downstream of the regulator. The generator's real power (kW) output was increased to a level greater than the kW load downstream of the regulator. The SVR rightly altered its mode of operation from forward to reverse, regulating the source-side voltage.

Subsequent to the successful outcome of the field tests the controls were fitted to an existing SVR situated on a distribution feeder with an 800kW hydro generator. The unit has successfully been in operation since January 1998.

CONCLUSIONS

As verified by the laboratory tests and the field experiments, the modification to the SVR control successfully senses reactive power flow. By using reactive power flow rather than real power flow to determine the direction of operation, this modified control design allows ESB to correctly regulate system voltage levels in the presence of embedded generation. ESB has determined that all future purchases of SVR control unit should incorporate the Reactive Bi-Directional Sensing capability.

ACKNOWLEDGEMENTS

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AUTHORS

James Foster is a Project Engineer with the Systems Engineering Group of Cooper Power Systems. His work includes capacitor and regulator application for power factor correction and voltage control, transient and harmonic field measurements, harmonic analysis, and harmonic filter design. He has been involved in industrial and utility studies using digital programs for system simulation and Cooper's Real-Time Power System Simulator (RTPSS) for real-time system analysis. Jim is a Registered Professional Engineer and a member of the IEEE Computer and Power Engineering Societies.

Craig Colopy is a Chief Engineer for the Step Voltage Regulator Product Line of Cooper Power Systems, involved in the development, design, and application of single-phase step voltage regulators for twenty-five years. Mr. Colopy is a working group co-chairman for the ANSI/IEEE Standard C57.15 for Step Voltage Regulators, and a member of Working Group 26 - Load Tap Changers of IEC-TC 14, Power Transformers. Craig is a Registered Professional Engineer and a member of the IEEE Computer, Communication, and Power Engineering Societies.

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