Grid Edge Control: A New Approach for Volt-VAR Optimization

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***Abstract*—A new approach to achieving volt-var control through the use of fast-acting distributed hybrid power electronics devices at the grid edge is proposed. It is shown that there is a missing layer of control at the grid edge which the conventional approaches do not address. Through field demonstration of 91, 10 kVAR devices on a 13 kV, 6 MW feeder, up to 5% CVR, 72% reduction in voltage volatility, 80% reduction in voltage unbalance and feeder level dynamic var control using the proposed grid edge control is presented.**

***Index Terms*—Volt-var control, volt-var optimization, electric distribution system, grid-edge, distribution automation**

I. Introduction

Under the American Recovery and Reinvestment Act (ARRA) of 2009 to modernize the US electric grid through deployment of smart grid technologies, the US Department of Energy has pumped almost $4.5 billion with a total value of $8 billion which includes contribution from the electric industry. Of this, $2.5 billion has been spent on distribution automation, volt-var control, conservation voltage reduction, energy conservation, peak demand reduction, and AMI deployment. With 200 participating utilities, this has been the single largest fund dedicated to modernizing the electric grid till date [1].

Duke Energy, reporting on the results of their ARRA deployments, shows that $155M/year in savings, representing 41% of the total savings came from voltage reduction, a direct use of volt-var control (VVC) techniques [2]. Other examples, such as Dominion's case to their regulators for a $500M AMI deployment showed that 80% of the economic justification was based on demand reduction and energy conservation based on VVC. Another study from McKinsey projects that $43B out of a total $63B in annual 'grid applications' benefits comes directly from VVC [3]. An additional $59B/year in benefits relate to peak demand management, energy conservation and avoided cost of new generation capacity – many of which can be impacted with volt-VAR optimization (VVO). It is abundantly clear that the economic justification for grid modernization often rests on using VVC as the vehicle to deliver improved system capacity, efficacy and revenues, while at the same time reducing operating and capital expenditures.

Even though VVC forms the majority of grid modernization return on investment, most of the utilities today are limited to achieving no more than 1-2% of control through conservation voltage reduction. This is due in part to the limited visibility on the secondary side of the grid, and the sparsity of control handles present in the form of line capacitor banks (LCB), line voltage regulators (LVR) and load tap changers (LTC) on the system. Further, the variability on the system arises on the secondary side of the distribution grid contributed by the dynamics of loads. However, the control resides on the primary side. Therefore, there is a missing layer of control on the secondary side of the grid, termed as the "grid-edge". In most cases, the voltage drops across the service transformers and the variability on the secondary side have been ignored or considered negligible. With increased AMI deployments, all these deep rooted assumptions are being proved wrong. Further, with the advent of distributed solar on the electric grid, the problem of voltage volatility and therefore VVC is becoming more complex. Consequently, a loss of VVO benefit is felt.

This paper introduces a new concept of achieving VVO through Grid Edge Volt-VAR control with the use of distributed dynamic power electronics devices that operate autonomously on the secondary side of the distribution system and eliminate the nasty variations that are seen due to poor power factor loads and other grid disturbances. A swarm of these grid-edge VVC controllers can act in unison to tame the grid into a well-behaved system and unlock a simple grid-edge VVC scheme to achieve 5-7% of energy and demand control, increase system efficiency by 10% and even provide feeder level dynamic lead-lag var control.

II. Limitations of Current VVC Approaches

Volt-VAR control can be broken down into three parts – *Sensing, Computing, and Control (or Actuation)*. In traditional Volt-VAR control methods, sensing occurs generally on the primary side where parameters such as, voltage, current, real and reactive power are measured. Information on these parameters is obtained either from the substation or through sparse locations on the network, generally at reclosers or cap banks along the feeder. One can imagine that the number of sensed parameters is generally in the range of 3-5. Recently, AMI data is being leveraged by some utilities and companies [4]. Even though AMI data seems to be the best "sensed" dataset one could use, there are some challenges associated with it. More often than not, voltage is not reported in addition to the kWh data. Even if reported, the rate at which AMI data is sent is generally in the 15 min to 1 hr range at best, sometimes as low as once or twice a day. Further, the voltage measured by most meters is a few cycle RMS (16 cycle is a common number). This cycle RMS measurement is time stamped at every 15^{th} minute or hour depending on the frequency of sampling, and therefore its use for making Volt-VAR control decisions seem to be too aggressive given that Utilities generally try to ensure compliance not within cycles but minutes. As is evident from the discussion, even if AMI data is leveraged for VVO, there are some severe limitation of the approach due to the quality and sparsity of data.

Once the sensed data is collected, most traditional systems perform an advanced optimization procedure using various constrained optimization techniques such as non-linear, mixed integer etc. The constraints are provided by the sparsely available control handles, generally 3 – 5 per feeder as mentioned before, in the form of LTCs, LVRs and cap banks. In one of the popular techniques for VVO, the optimization is iteratively run with a load flow solution of the network which computes estimation on secondary voltages. The load flow solution starts with an assumption on load allocation based on the total MW and MVAR at the substation. It then iteratively improves the results based on the feedback obtained from some of the primary side sensed information. Once converged, the results are passed on to the optimizer which computes the optimal tap positions for line voltage regulators, capacitor banks switching sequence and changes in LTC if needed. Even though this approach provides a fairly advanced method of performing VVO, at the most fundamental level, it begs to re-visit the core assumptions.

It seems that load allocation is one of the most important functions in this algorithm as it directly provides the voltage profile along the feeder. Therefore, accurate model becomes one of the most important requirements to ensure accuracy of results. Further, mathematically estimating 100s of unknown parameters with 3-5 known parameters is bound to have large errors and is something that the industry acknowledges. Therefore, unless one uses real-time AMI data reads or historical load data and load forecast in addition to the few parameters being monitored on the grid, this approach only provides a highly sub-optimal solution at best. Other approaches that tend to use a “non-model”, “heuristic” or “advanced regression based” method in addition to the AMI data would perform relatively better. However, with a purely heuristic approach without considering the physics of the problem one may quickly lose sight of the real physical constraints.

Finally, whichever approach is used, model-based, rule-based, LDC based, EOL sensing based or AMI based, all these approaches rely on the sparsely deployed primary side assets for affecting control and actuation. While, the voltage constraints used in most of these approaches is the ANSI limit which applies to the low-voltage side of the service transformer, specifically the service entrance (120 / 240 V side), clearly depicting lack of control. Further, as the life of the assets being used on the primary side is deeply impacted by the number of times they are operated, e.g. switched on/off in the case of cap banks and number of times tap positions changes in a day for LVRs and LTCs. With the advent of distributed solar PV, the number of LTC operations is expected to go up so much that the life could be impacted from 30 years to 3 years [5]. Therefore, most algorithms are also constrained by the number of operations. These constraints further limit the results of the optimization, for instance, if the optimizer is run once every 30 minutes, and the number of switching limit on a certain cap bank is 10 times a day, then in the worst case, the capacitor bank could be used up in the first 5 hrs of the day and be a completely uncontrollable asset for the rest of the 19 hrs.

Given the above discussion, one very quickly starts to appreciate the limits and constraints that are put on such algorithms due to lack of sensing and control on the secondary side of the distribution grid.

III. Missing Grid Edge Control Layer

The fundamental assumption that Utilities and VVO providers have generally assumed the level of variability at the individual customer load and the drop across the service transformer to be small. Further, most of the occurrences of low voltage are assumed to be at the end-of-line (EOL). To validate these assumptions, let’s try to create a physical model of the grid edge, essentially a service transformer connected to a load. Let’s call this the local “local grid-edge model” as shown in Fig. 1.

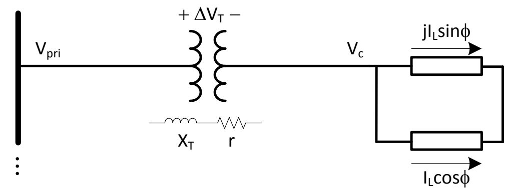

Fig. 1. (a) Representation of a typical load connected through a distribution transformer to the grid.

At any instant in time the drop ΔV_T across the transformer can be expressed as,

$$\Delta V_T = I_L X_T \sin\phi + I_L r \cos\phi + j\left(I_L X_T \cos\phi + I_L r \sin\phi\right) \quad (1)$$

For relatively small ϕ, the impact of the quadrature component of the voltage drop across the transformer is quite small and can be neglected. Further, $\cos\phi$ and $\sin\phi$ terms can be represented as a function of power factor PF,

$$\Delta V_T \approx I_L X_T \sqrt{1-PF^2} + I_L r PF \quad (2)$$

Eq. 2 clearly demonstrates that the voltage drop across the distribution transformer changes significantly as a function of load level, power factor and transformer impedance. Taking a typical X/r ratio for a distribution transformer of 3-5, the voltage drop at full load and unity power factor load is around 1%. However, at poor power factor or heavy loading conditions, the voltage drop is dominated by the inductive component and can be very large, as high as 2-5% in some cases. As currents vary by over an order of magnitude over the course of a day, with power factors that vary from unity to as low 0.7, voltage drops in the 1 – 5% of the line voltage or almost half of the allowed ANSI band are expected. This causes the minimum voltage point along a feeder to not be at the end of the feeder, but at arbitrary locations along the feeder, depending on the transformer impedance and loading level at a particular time. This does not seem to have been anticipated, but has been validated by many utilities that have been examining their AMI data. Data collected from the field exemplifies the argument in Fig. 2.

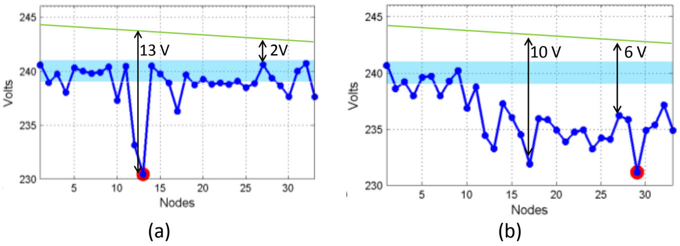

Fig. 2. Dark blue line shows the measured secondary voltage profile along an actual feeder with 33 nodes. (a) Minimum voltage occurs at node 13 at 10 pm. (b) Minimum voltage occurs at node 29 at 11 pm

It is abundantly clear that it is indeed the grid edge where most of the grid-issues arise, most of the sources of the variability originate, and it is at this grid-edge where today no control is present, see Fig. 3 for an illustration.

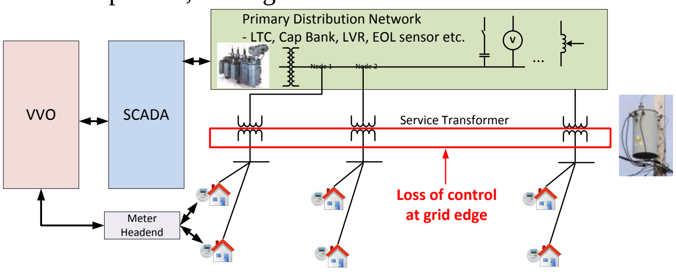

Fig. 3. Conventional VVC systems with lack of control at the grid edge

IV. GRID-EDGE VOLT-VAR CONTROL

The patented Edge of Network Grid Optimizer (ENGO) from Varentec provides the much needed layer of control at the grid edge. ENGO is built using capacitors controlled with smart switches for injecting varying levels of reactive power in the grid [6]. The ENGO device takes a voltage set-point as an input and dynamically injects the right amount of reactive power to achieve voltage regulation. The device is rated at 0-10 kVARs (single phase) and is directly connected at the grid edge on the secondary side of distribution transformers. Featuring sub-cycle response, the unit corrects 2-13 volts at individual node, and features low loss (35 watts), low weight (35 lbs), and is designed with a long life (15 years). A swarm of these devices can be operated with a simple broadcast of a voltage set-point, requiring no peer-to-peer communication to achieve multiple control objectives at a feeder level. These devices are managed by supervisory software called the Grid Edge Management System (GEMS), which performs secure data collection and management, visualization and analytics, over-the-air upgrade and control of the entire swarm of devices. The communication between the ENGO-V10 and the GEMS platform can be very slow and intermittent as the device once given an objective function tend to operate autonomously without any supervisory control in a completely distributed fashion. Fig. 4 depicts a typical field installation and how these devices can help provide a layer of control at the grid-edge.

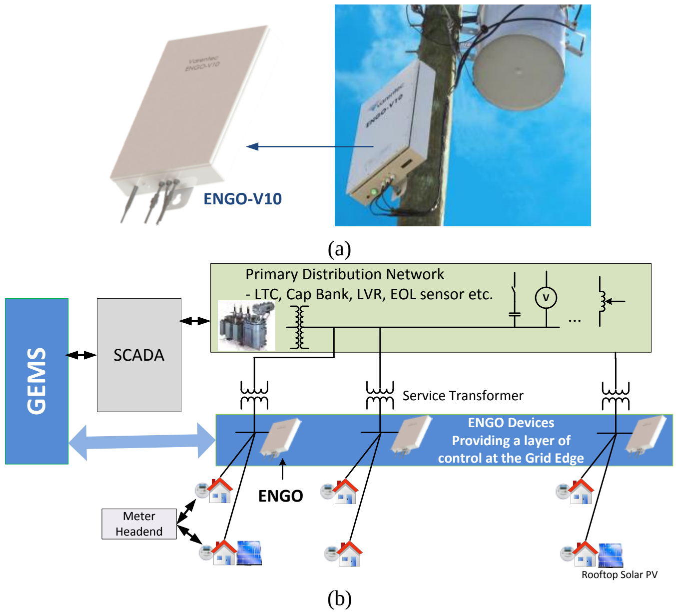

Fig. 4. (a) ENGO-V10 is installable on a pole-top next to the service transformer, (b) System architecture showing ENGO and GEMS providing the much needed layer of control at the grid edge

A. Local Grid-Edge Control

To understand the behavior of these grid-edge ENGO devices, let's re-visit the grid edge model introduced in Fig. 1. But, this time we include a single ENGO unit at the secondary of the service transformer. When commanded with a setpoint V_{sp} through the GEMS platform by the Utility operator, the ENGO unit autonomously regulates the secondary voltage V_c to V_{sp} regardless of the primary voltage V_{pri}. Essentially the secondary side of the transformer gets transformed into a controlled voltage source with a magnitude equal to V_{sp}. As the impact of a single unit on the primary side is negligible, the grid-edge model can be reduced to a synchronous machine model where two sources V_{pri} and V_{sp} are separated by the leakage inductance of the transformer as shown in Fig. 5b. The var flow through the transformer is given by

$$Q_{ps} = \frac{V_{pri}\left(V_{pri} - V_c\right)}{X_T}, \text{ where } V_c = V_{sp} \text{ within the control range}$$

In general, by increasing or decreasing the setpoint voltage of the ENGO with respect to the primary voltage V_{pri}, Q_{ps} can be made lagging, leading or zero,

$$Q_{ps} = \begin{cases} Lagging, & V_c > V_{pri} \\ 0, & V_c = V_{pri} \\ Leading, & V_c < V_{pri} \end{cases} \tag{3}$$

The characteristic curve of a single ENGO unit is shown in Fig. 5c. The black curve shows the voltage profile as the primary voltage changes without the presence of ENGO unit. With the ENGO unit present and operating at Vsp = 240V, the red curve shows the voltage profile at the secondary side as the primary voltage varies over 230-250V. It can be seen that the voltage is significantly boosted over the entire low voltage range, and between 235 – 244V the voltage is precisely controlled at 240V. Finally, the most intriguing aspect of the characteristic is lead-lag var control with a leading var control device represented by the green curve. It is seen that the ENGO unit can be used to control var flow on the grid by changing its setpoint voltage. As theorized, when the voltage setpoint of the ENGO unit is equal to the primary voltage, the var flow across the transformer is almost zero, represented by the red dot.

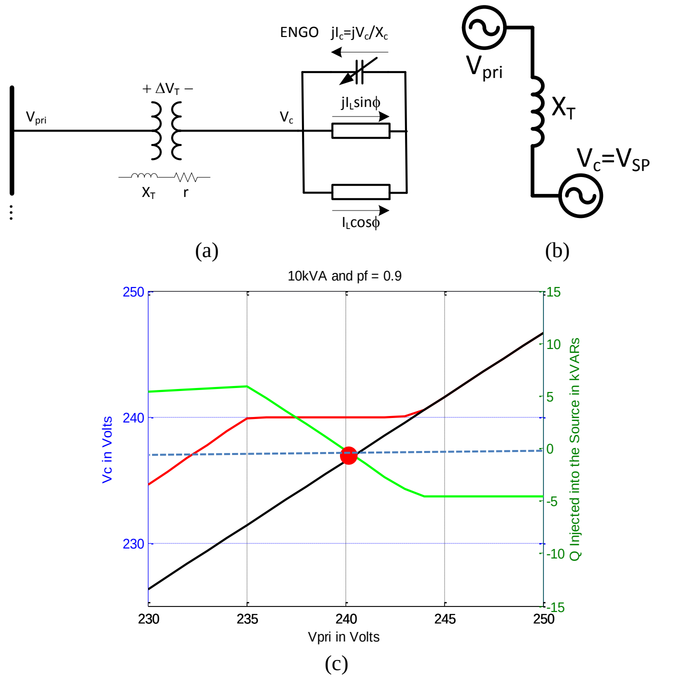

Fig. 5. (a) Grid edge model with ENGO unit connected and regulating the secondary voltage Vc to a setpoint V_{sp}, (b) Grid edge level 'Synchronous machine' model of (a), (c) characteristic curve of ENGO device

B. Feeder Level Grid Edge Volt-VAR Control

To control the entire feeder, a swarm of ENGO devices is required to be optimally distributed across the entire system. As a rule of thumb, 7-15% per peak MVA of the feeder is required to be covered to ensure complete controllability. The mechanics behind the control philosophy is expounded next.

With a swarm of ENGO devices present on a distribution feeder (or a collection of feeders), assume that all the devices are operating with the same setpoint Vsp. Consider a scenario where the primary voltage is less than the setpoint voltage Vsp. In such a situation, leading vars from the secondary will flow to the primary as per eq(3). Vars from other ENGO units on the feeder will sum up on the primary and try to raise the primary voltage. As soon as the primary voltage becomes equal to the secondary, vars will stop flowing and an equilibrium will be reached. A similar argument holds when the primary voltage is higher than the setpoint, in which case, vars will flow from primary to secondary and cause the primary voltage to reduce, and utlimately equilibrium will be reached when Vpri = Vsp. This unexpected and very unique network effect causes the entire feeder to achieve the same voltage as the ENGO setpoint voltage. This aggregated effect due to the swarm of ENGO devices causes a “passive self-balancing” of the system and is at the heart of achieving a simple control of this very complex system [7]. As a by-product, the primary side capacitor banks, LVRs and LTCs switch less and their life increases.

The entire feeder once again reduces to the ‘synchronous machine’ model similar to that in Fig. 5b, where now the LTC voltage V_{LTC} and V_{sp} are the two sources, and X_{eq} is the equivalent impedance between them. There are now two independent levers, V_{LTC} and V_{sp}, for controlling the reactive flow from the substation Q_{sf}, given by:

$$Q_{sf} = \frac{V_{LTC}\left(V_{LTC} - V_{peq}\right)}{X_{eq}}, \text{ where } V_{peq} = V_{sp} \text{ within the control range}$$

C. Feeder Level Control - Summary

With a simple voltage setpoint control, a very complex system with a multitude of devices and assets can be made to behave in a stable and controllable manner to achieve system level objectives in a completely decoupled fashion. Voltage control is achieved using dispatch of the same setpoint V_{sp}, reactive power is controlled using the difference in voltage between V_{LTC} and V_{sp}, and the real power is controlled using the common mode voltage $(V_{LTC}+V_{sp})/2$.

V. Field Demonstration

Varentec has proved this new concept of grid edge control through many pilot projects with several utilities with more than 700 ENGO units deployed. As part of these projects, the various objectives of VVO such as energy conservation through 24x7 CVR, peak demand reduction, voltage support and increase in quality of power are being demonstrated. Key field results that exemplify the fundamental premise of control discussed in this paper have been presented next.

A. Voltage and Real Power (and Energy) Control

Grid-edge control was validated on the 13 kV / 6 MW peak Omega feeder on the Southern Company network. A total of 91 ENGO-V10 devices were distributed along the feeder, representing a maximum of 910 kVARs in VAR injection. The feeder has two cap banks, one switched (900 kvar) and one fixed (600 kvar). Fig. 6a shows the voltage profile along the feeder when the LTC was fixed at 247V and all the ENGO units were off (monitoring mode) over an 8 hour period. The voltage at the substation is shown as the blue trace. The red/orange traces show voltages at 24 distinct locations on phase B which evidently shows low voltages due to a fixed cap bank fuse failure. Fig. 6b depicts a similar day with the LTC at 240V (3% CVR) setting. Significant ANSI voltage violations are observed for extended duration without ENGO devices. A large gap between the substation bus voltage and the node voltages along the feeder is observed. Further, as expected upto 18 V of volatility is observed between the different traces. Fig. 6c shows a similar day with ENGO units turned On and operating with the same setpoint as the LTC (240V). It is immediately clear that the gap between the substation bus voltage (blue curve) and the grid edge voltages along the feeder is almost completely removed. Further, the variability between the different nodes is reduced to almost 5V. Finally, Fig. 6d shows a further 2% reduction in the LTC (total of 5% CVR). With the ENGO units regulating the voltage to the setpoint, the entire feeder, even locations not monitored or controlled by the ENGOs, achieve the same voltage level as V_{sp}. These results clearly show the "passive self-balancing" property discussed in the previous section. In addition, in this demonstration the grid edge control also helped to reduce voltage unbalance by 80% between phases and reduce voltage volatility by 72%.

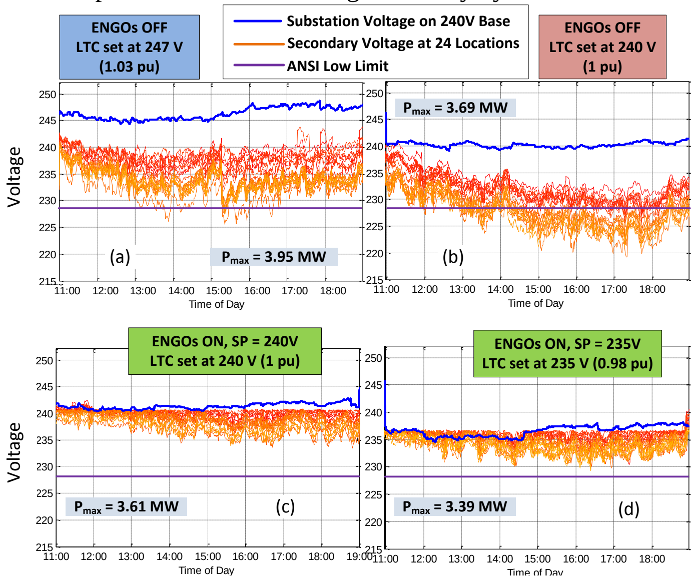

Fig. 6. Field data shows (a) baseline voltage plot (b) conventional 3% CVR, (c) and (d) 3% and 5% CVR respectively with grid edge control using ENGO

B. Reactive Power (VAR) Control

Fig. 7 shows voltage measured and reactive power data captured at the substation on two consecutive days. For 8 hours (from 11 am to 7 pm) everyday, the LTC voltage was reduced from 247V to 235V. Concurrently, ENGO setpoint voltage was also set at 235V during these 8 hrs. For the remaining 16 hours in the day, the LTC voltage was at 247V, and the ENGO units were kept in the monitor-only mode or in other words were OFF. It can be observed in Fig. 7 that when ENGO devices are OFF, there is a difference in reactive power between phases A, C and B, which was shown to be due to a blown fuse on the phase B fixed capacitor bank. When the voltage setpoint of both the LTC and the ENGO devices is set at 235 volts, it is seen that the difference in reactive power between all phases disappears. In this mode, the feeder level VAR loading for all phases is regulated to 250 kVAR leading, indicating that the net contribution of VARs from the ENGO devices is maintained at zero even as load kW and PF vary over the day. The VAR offset of 300 kVAR leading is due to the switched capacitor bank which is controlled based on locally sensed voltage, switching ON when the voltage goes below 237 volts.

VI. CONCLUSIONS

A new concept of volt-var control, namely Grid-Edge Control was introduced in this paper. The approach makes use of distributed hybrid power electronics devices called ENGO that operate at the grid-edge and autonomously regulate the voltage to a setpoint. These devices can be managed via a supervisory system called the GEMS through slow communication to achieve volt-var objectives such as 5-7% energy and demand control, 10% reduction in system losses, and fast lead-lag var control at the substation through a simple setpoint dispatch. Varentec has deployed several hundred ENGO units in the field and is currently demonstrating many such VVO objectives with different utility partners. Results from one such demonstration at Southern company with 91 ENGO devices on a single feeder to achieve 5% CVR and fast reactive power control was presented.

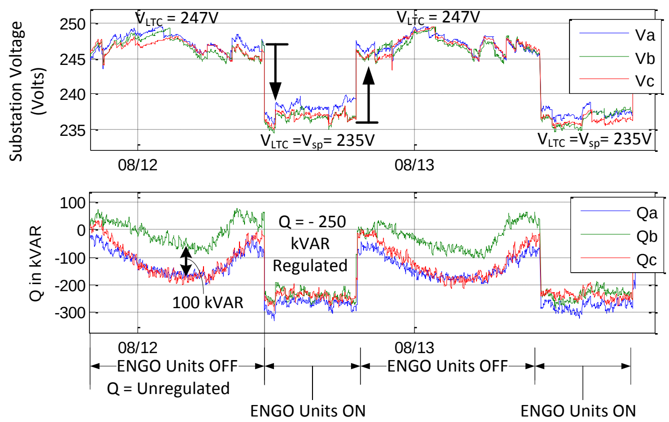

Fig. 7. Field data showing reactive flow at the substation as a function of time, with ENGO units OFF Q is unregulated; while with 91 ENGO units ON, Q is controlled to -250 kVAR -Distribution Feeder Behaves like a STATCOM

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