GRIDCO SYSTEMS™

A NEW ERA IN ACTIVE GRID INFRASTRUCTURE

Putting Power Electronics Solutions to Work for Distribution Utilities

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WHITE PAPER

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EXECUTIVE SUMMARY — THE ADVENT OF *ACTIVE GRID INFRASTRUCTURE*

In order for distribution operators to maintain a reliable and efficient power delivery system in the face of increasing adoption of distributed energy resources, increasing transmission capacity constraints, and increasing frequency of severe weather systems, they must begin migrating towards an *Active Grid*, one that is *Distributed*, *Dynamic*, and *Decoupled* in nature; *Distributed* to address the spatial asymmetry of load growth and distributed energy resources, *Dynamic* to address the decreasing time scales and increasing magnitudes of power quality deviations, and *Decoupled* in order to ensure system-wide stability and operational simplicity.

As described in our previous whitepaper, "Intelligent Power Management and the Future of the Distribution Grid," a *Distributed* power regulation solution is necessary to address the observability and controllability challenges associated with traditional centralized solutions. Furthermore, it is difficult to meet *Dynamic* requirements, driven by intermittency of renewable power, for example, with conventional electro-mechanical equipment without sacrificing reliability and device lifetime; an undesirable trade-off that distribution operators are already facing today. Finally, a *Decoupled* architecture is required to effectively segment the grid into regulation zones that can simplify the operation and increase the stability of the grid. The requirements of an *Active Grid* are clear. What have been missing are practical solutions to satisfy these emerging needs.

MEETING THE TECHNICAL AND ECONOMIC REQUIREMENTS OF THE ACTIVE GRID NECESSITATES THE USE OF SERIES-CONNECTED, VOLTAGE-CONTROLLED POWER REGULATION PLATFORMS

The imminent availability of commercially viable, utility-scale *power electronics* to address these needs changes the game and represents a fundamental supply-side shift in the utility industry, one that will transform the distribution feeder architecture not only for the better, but forever. However, with all new technologies come critical decisions regarding their most effective use. Wholesale replacement is rarely the answer, so the challenge, and indeed opportunity, is one of augmenting existing assets with judicious adoption of new technology targeted at critical, and growing problems. In this regard, the intrinsic flexibility of *power electronics* offers numerous options for consideration, some of which will prove more viable than others. Successful application of utility-scale *power electronics* systems for the distribution grid will be driven by the identification of those specific approaches that simultaneously deliver cost-effective, efficient, and reliable platforms for the primary functions of dynamic and continuous voltage regulation over a wide range, power factor correction, and harmonic cancellation. Moreover, the business case for such systems must not rely on financial subsidy or intangible societal benefits. Rather, new solutions must entail lower overall capital expenditures than conventional solutions, while unlocking operational savings and adapting to evolving demands.

Meeting these technical and economic requirements necessitates the use of *Active Grid Infrastructure* consisting of *series-connected, voltage-controlled* power regulation platforms. Amongst the family of candidate power regulation architectures, the series-connected, voltage-controlled design is unique in its ability not only to provide the widest *dynamic* voltage regulation range at the lowest capital cost, but also to maintain grid-wide stability via the *decoupling* of primary and secondary feeders. These attributes also encourage the *distributed* use of power regulation at exactly the points where it is most needed. Alternative architectures, based on shunt-connected, current-controlled system building blocks, do not satisfy all of these requirements. Even so, these configurations will also prove useful to overall power regulation, but in a supporting role for power factor correction and harmonic mitigation.

As will be described in this white paper, by leveraging advancements in *power electronics* in conjunction with prudent system design, it is now possible to build a new class of commercially viable, utility-scale power regulation systems that enable *Distributed, Dynamic,* and *Decoupled* functionality. A new era of *Active Grid Infrastructure* is upon us, and given the challenges ahead, it is most timely indeed.

THE MISSING INGREDIENT FOR AN *ACTIVE GRID*

True grid modernization entails more than just upgrading existing assets, deploying communications and data analytics systems, and installing sensing and metering infrastructure. The continually evolving demands placed on the electric grid resulting from increasing penetration of distributed energy resources, increasing transmission capacity constraints, and increasing grid reliability challenges, require a new class of *Active Grid Infrastructure* that enables utilities to economically address the challenges of today, while providing reliable and scalable adaptation to the challenges of tomorrow. Inherent in these solutions is the ability to respond to time-varying grid conditions through adaptive, localized, and continuous power regulation, thereby providing the fundamental, indeed novel, function of *real-time power quality assurance*. Herein lies the essential economic value proposition to utility, regulator, and customer — one that is rooted in systemic reliability and efficiency enhancements, lower capital expenditures as compared to traditional grid reinforcement solutions, and one that does not rely on financial subsidy or intangible societal benefits to render it whole.

The technical challenges and applications already driving the need for *active power regulation* are outlined in Table 1. As described in our previous white paper, these demands dictate the use of power regulation infrastructure that is *Distributed* in control, *Dynamic* in response, and provides for architectural *Decoupling* of the distribution feeder.

Table 1— Voice of the Distribution Utility

APPLICATIONS	CHALLENGES FACED BY DISTRIBUTION ENGINEERS
SYSTEM STABILITY & FLEXIBILITY	“We try to optimize voltage profile, load balance, system losses, and power factor at all times” “We strive to reduce number of customers interrupted and improve service restoration time”
VARIABLE RENEWABLE GENERATION	“We don’t know if we’re delivering voltage at the right levels at all times” “Our mechanical devices are operating too frequently”
CHANGING LOADS	“Existing approaches are too centralized – don’t ‘see’ the problem” “Need finer tools closer to loads”
CVR / ENERGY EFFICIENCY	“Increasingly difficult to maintain CVR targets with existing solutions, especially with PV, circuit reconfiguration and long lines” “Receiving more customer complaints as we try to lower substation voltage”
DEMAND RESPONSE	“We need a more dynamic and reliable demand response capability” “We prefer not to rely on customer participation”
POWER QUALITY	“Customers are increasingly sensitive to sags/swells” “We are getting more complaints from FIT and non-FIT customers”

HOW IS GERMANY ADDRESSING THE PV INTEGRATION CHALLENGE?

By the end of 2012, Germany had over 32 GW of cumulative PV capacity installed, representing over 30% of the world’s total installed PV capacity.[1] In response to the dynamic supply/demand challenges that photovoltaic and wind power sources have brought about, “smart” inverters have been deployed (or correspondingly retrofitted) with two important system level functions: low-voltage ride-through and wider operating frequency ranges. These functions are required to avert tripping of distributed PV resources when they are needed the most — when generation supply cannot meet demand.

Interestingly, however, the vast majority of German Distribution Network Operators have chosen **not to** enable the reactive power compensation capabilities of “smart” inverters to support grid voltage in either autonomous or centrally managed mode, especially at the residential level. This is largely due to three reasons. First, the effectiveness of VAR support for voltage regulation is diminished with the lower “X/R ratios” associated with cable (underground or overhead) used in Europe as compared to North America. Second, the autonomous VAR approach relies on a “blind” injection of VARs per Watt delivered. This leads to accumulation of unnecessary VARs and losses as seen at the secondary substation. Third, much work still needs to be done to implement a reliable communication infrastructure to manage the remote adjustments that will be required for optimization and stability. Until such communications standards are established, these adjustments would likely require continuous “physical reprogramming” of set points by field personnel.

Because of these limitations, an alternative and complementary approach to “smart” inverters is being specified and implemented. This approach focuses on utility-owned, utility-managed series-connected voltage regulation solutions located at the secondary substation and in-line along secondary feeders. This approach solves many of the voltage regulation issues, while avoiding the technical concerns and operational risks associated with relying on approaches based on VAR support.

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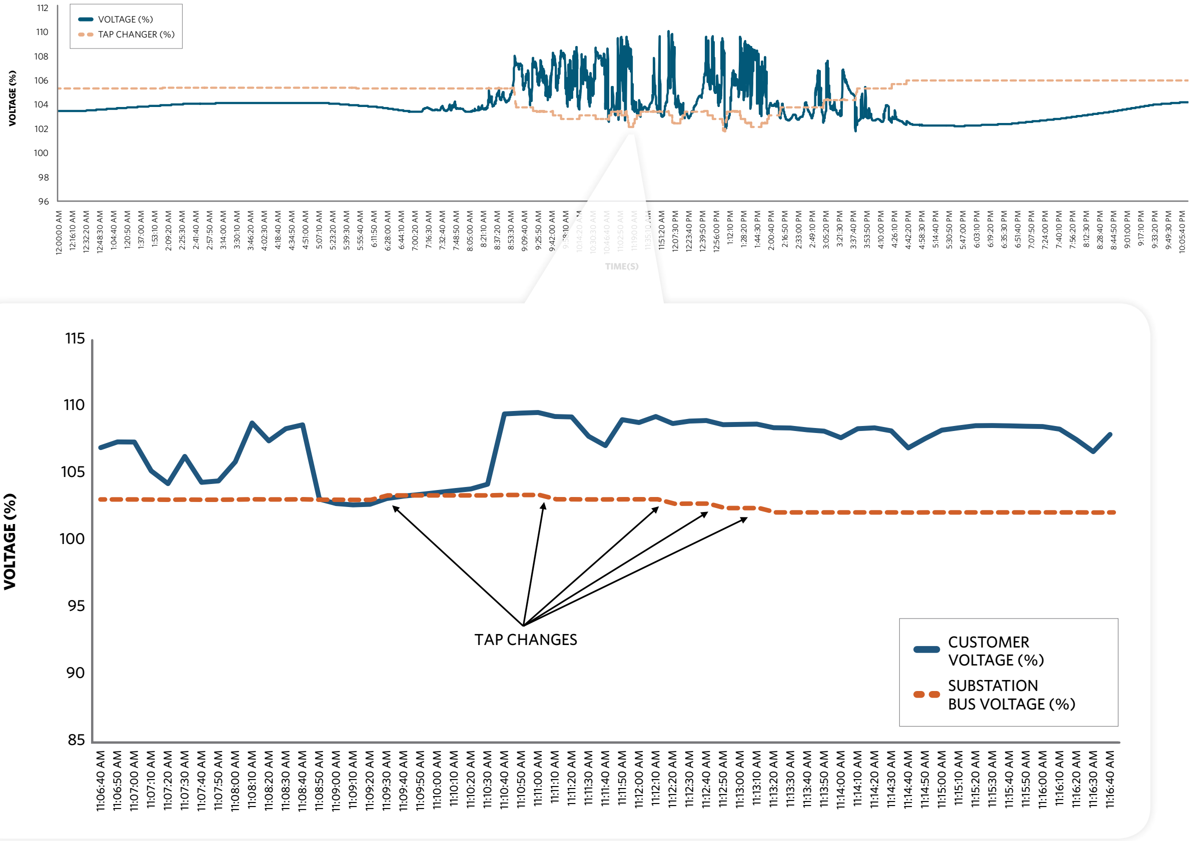
[1] European Photovoltaic Industry Association’s (EPIA) “Global Market Outlook For Photovoltaics 2013-2017”

Historically, utilities have built distribution feeders according to design rules intended to ensure voltage compliance *with high probability* at the point of common coupling. Such rules enabled distribution engineers to dimension the length and gauge of feeder lines, and to locate electromechanical devices like tap changes, line regulators, and capacitor banks on the primary feeder to maintain a desired feeder voltage profile. Indeed, the primary feeder voltage profile has historically been a reliable proxy for voltage delivered at the point of common coupling, so long as underlying load assumptions hold true and sufficient, but costly, margin is built-in. However, geographically asymmetric load growth, coupled with the adoption of customer and utility-owned distributed generation sources, break the assumptions underlying these design rules and, consequently, have resulted in increasingly frequent violations of regulated voltage standards. Moreover, the presence of such violations can now routinely be confirmed in distribution feeders augmented with metering and sensing devices. Further exacerbating this challenge is the fact that distributed energy resources cause rapid time variation in voltages closest to the point of common coupling, as depicted in Figure 1. Traditional line-oriented electromechanical devices are incapable of reliably regulating voltage on these time scales and at the locations of most interest.

Figure 1 — Rapid Voltage Variation Causing Over-Actuation of Load Tap Changer



The *observability* and *controllability* challenges associated with line-oriented power control devices are already leading utilities to the use of *Distributed* (secondary-side) sensors and voltage regulation devices in order to maintain compliance with voltage standards, not just with high probability, but with *real-time assurance*, as described in the text box above. Although electromechanical technology can, in principle, be leveraged for secondary-side voltage regulation through the use of on-load tap-changers for example, such devices suffer from operational lifetimes that decrease with every actuation cycle, response times in the range of tens of seconds, and coarse voltage steps on the order of +/-2.5%. Stated another way, the response of electromechanical voltage regulators is not only slow and discrete, but exhibits an intrinsic trade-off between regulation speed and device lifetime. Indeed, utilities facing high penetration of distributed energy resources are seeing actuation of electromechanical devices at up to 10x the rate they were designed for and requiring replacement 2-3 times more frequently than expected. Given that this performance vs. lifetime trade-off fundamentally arises from the use of mechanical actuation techniques, one would naturally be inclined to ask the question: is it possible to provide dynamic power regulation over a wide operating range via something other than electro-mechanical technology?

POWER ELECTRONICS, THE FOUNDATION FOR *ACTIVE GRID INFRASTRUCTURE* AT UTILITY-SCALE

Despite its far-reaching adoption to date, *power electronics* technology has seen limited deployment within utility-scale power distribution systems. Although inherently capable of providing dynamic and continuous response without sacrificing device lifetime (in contrast to electromechanical solutions), the primary challenge in applying *power electronics* to utility-owned infrastructure lies in optimizing system design to simultaneously meet the following essential criteria:

a) Cost competitiveness with existing alternatives

b) System efficiency ~99%

c) System lifetime in outdoor environments ~25 years

d) Wide power regulation range of +/-10%; buck and boost

e) Functional flexibility — voltage regulation, VAR control, harmonic mitigation, and more all in one platform

f) Operational simplicity — maintenance-free; operate autonomously in a ‘set and forget’ mode or seamlessly integrate into a centralized SCADA/DMS-based management scheme

g) Deployment flexibility — small volumetric footprint and easy to install.

ABOUT POWER ELECTRONICS

Power electronics refers to the application of semiconductor switching devices to the **conversion and control of electric power**. Although related in origin to the field of microelectronics, power electronics is distinct in that its primary focus is on the efficient manipulation of large quantities of electrons for the purpose of power flow control, as opposed to relatively few electrons for the purpose of information processing. The use of semiconductor switching devices, rather than electro-mechanical switching devices, for power processing purposes provides for fast, continuous, multifunction operation without sacrificing device lifetime.

In contrast to microelectronics where **application value** is derived primarily from increasing circuit complexity (think computer microprocessors, internet routers, and consumer electronics), application value in power electronics has generally been derived from increasing needs for power quality, control, and efficiency in a minimal volumetric footprint. The numerous benefits of power electronics have spawned innovations in materials, devices, packaging, and controls.

Since the invention of the transistor in 1947, advances in power electronics have accelerated and delivered benefits in almost every industry imaginable. Audio amplifiers, cellular communications, microwave ovens, plasma TVs, battery chargers, fluorescent lamps, uninterruptable power supplies, hybrid electric vehicles, electric trains, and inverters for photovoltaic, wind and storage systems are just a few of the many products and applications enabled, in large part, by advances in power electronics. The benefits that power electronics bring to these applications are solid-state design (no moving parts), small size, efficiency, fast response (sub-cycle), and continuous operation (high fidelity output). Recent industry reports estimate the worldwide power electronics market to reach $130B in 2015. All of us rely on power electronics every day.

Over the last decade, advances in materials, devices, and packaging have provided the hardware building blocks necessary to construct power converters at scales of relevance to distribution utilities (10 KVA < P<10 MVA). Indeed, PV inverters, wind converters, and motor drives for hybrid electric vehicles have driven and leveraged much of this advancement. However, one must adopt these device advancements within a *system architecture* capable of meeting all the criteria listed above.

A SYSTEM ARCHITECTURE FOR UTILITY-SCALE ACTIVE POWER REGULATORS

One of the benefits of power electronics is its inherent multi-functional capability. Commercially viable products will be based on system architectures that rely on the minimum capacity of power electronics necessary to provide the desired power regulation functions, such as those listed in Table 2. By far the most critical function needed to address today's applications is dynamic and continuous voltage regulation over a broad range.

Table 2 — Broad Range of Functionality Enabled by Power Electronics

FUNCTION	DESCRIPTION AND BENEFITS
VOLTAGE REGULATION	Dynamic, continuous boost and buck up to +/-10% to ensure ANSI C84.1 and EN 50160 voltage compliance, and achieve CVR voltage targets
HARMONIC COMPENSATION	Voltage and current harmonic cancellation to improve power quality
PHASE BALANCING	Voltage and current balancing to reduce inefficiencies
PHASE ANGLE REGULATION	Control of power flow among parallel lines or equipment

MAKING THE ECONOMIC AND EFFICIENT CHOICE

As outlined in Figure 2, voltage regulation can be performed either directly via voltage control or indirectly via current control. Voltage regulation through *current control* is based on the injection or absorption of reactive power, and the impact of such reactive power on the feeder voltage profile through its interaction with upstream system impedance. Capacitor banks, STATCOMs, and solar inverters are all examples of current-controlled devices, and are all shunt-connected (parallel) to the feeder. In this case, the degree of achievable voltage control, or equivalently the dynamic range of voltage regulation, is a function of the feeder's impedance upstream of the current-sourced device. As a result, they are unable to *directly* control voltage at their location, but rather *indirectly* influence local voltage through their manipulation of reactive power. The lower the system impedance, the more reactive power is required to have a meaningful effect on local voltage.

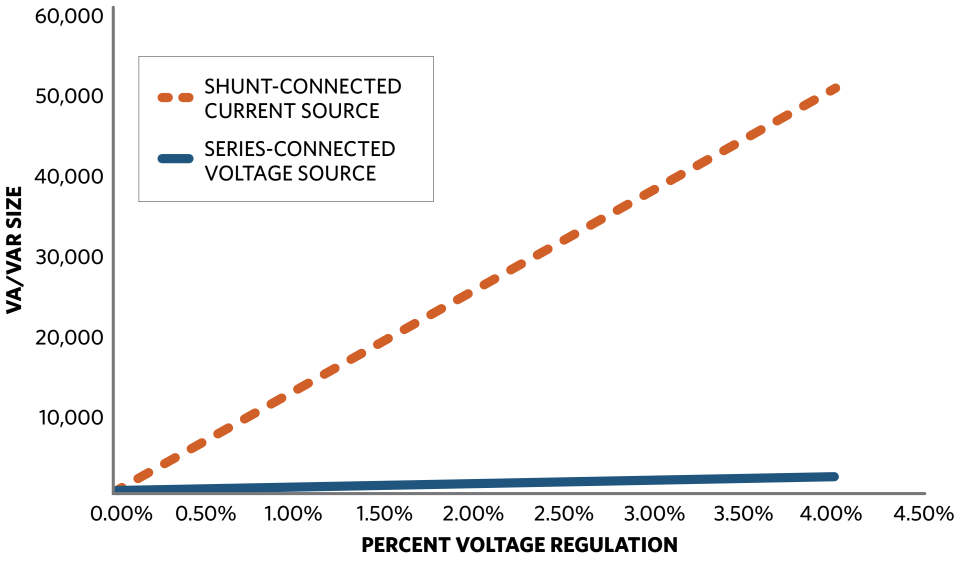
> *EVEN FOR SMALL VOLTAGE REGULATION RANGES, A CURRENT-CONTROLLED ARCHITECTURE REQUIRES AN ORDER OF MAGNITUDE MORE POWER ELECTRONICS.*

***Figure 2* — Voltage Control Methods**

	METHOD	DEVICE
DIRECT	VOLTAGE CONTROL (Series-Connected)	Load Tap Changer Line Regulator
INDIRECT	CURRENT CONTROL (Shunt-Connected)	Capacitor Bank D-STATCOM / SVC Smart Inverter Energy Storage

In contrast, voltage regulation through *series voltage control* is based on the direct addition or subtraction of voltage via controllable elements that are connected in series with the feeder. Prime examples of series voltage-controlled devices are line regulators and on-load tap changers which create a voltage step between input and output by mechanically altering the turns-ratio of a transformer. In contrast to current-controlled devices, series-connected voltage-controlled devices impact voltage downstream of them, but have no effect on the feeder voltage upstream of them. This is of particular importance since the voltage of interest in relation to compliance with the relevant standard (ANSI C84.1 Rule 2, EN 50160) is the voltage at the point of common coupling, *downstream of distribution transformers*.

***Figure 3* — VA Rating Required for Voltage Regulation**



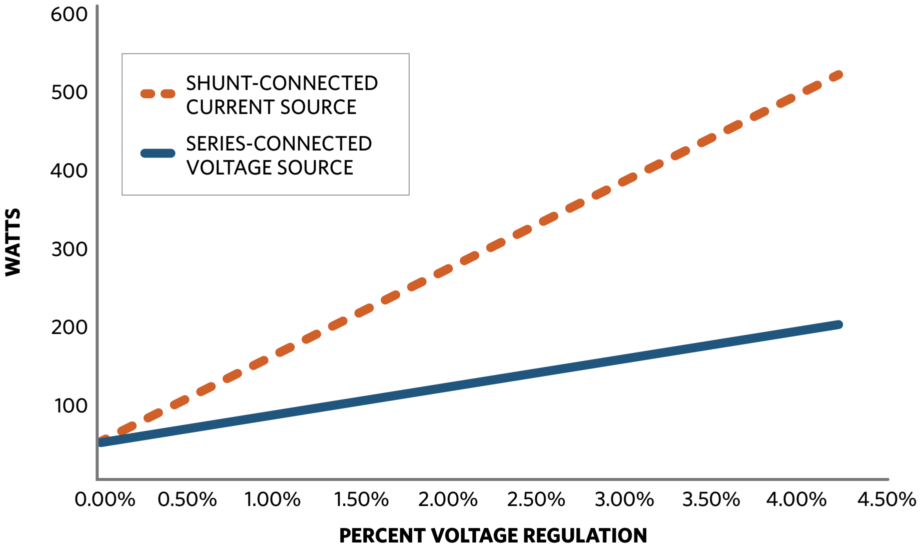
(Base=50kVA; Z=4%; X/R=1.5)

Given the desired degree of voltage regulation at the point of common coupling, one can readily calculate the capacity of power electronics required for a shunt-connected, current-controlled device vs. a series-connected,voltage-controlled device, assuming the location of such a device to be on the secondary-side of a distribution transformer. Referring to Figure 3, one can see that even for small voltage regulation ranges, relying on a current-controlled architecture requires an order of magnitude more power electronics than a series voltage-controlled architecture. Fundamentally, this large difference arises from the fact that a current-controlled device relies on the impedance of the feeder to induce a voltage change, whereas a series voltage-controlled device directly 'inserts' the desired voltage change. It comes as no surprise then that capacitor banks (shunt-connected, current-controlled devices), which can be used to influence voltage, are typically sized on the order of many 100s of kVAR in order to have an appreciable impact on line voltage.

Capacitor banks, STATCOMs, and solar inverters are all examples of current-controlled devices, and are all shunt-connected (parallel) to the feeder. In this case, the degree of achievable voltage control, or equivalently the dynamic range of voltage regulation, is a function of the feeder's impedance upstream of the current-sourced device. As a result, they are unable to *directly* control voltage at their location, but rather *indirectly* influence local voltage through their manipulation of reactive power. The lower the system impedance, the more reactive power is required to have a meaningful effect on local voltage.

It should additionally be noted that a power regulation device's internal conversion losses scale with the capacity of power electronics they employ. As such, current-controlled devices also exhibit lower system efficiencies than series voltage-controlled devices for an equivalent degree of voltage regulation, as depicted in Figure 4. *One can thus conclude that in order for a power electronics-enabled voltage regulation platform to be effective, economically viable, and systemically efficient, it must necessarily rely on a series-connected, voltage-controlled architecture*.

Figure 4 — Power Losses for Voltage Regulation



(Base=50kVA; Z=4%; X/R=1.5)

FEEDER **DECOUPLING** WITH THE SERIES-CONNECTED VOLTAGE SOURCE ARCHITECTURE

In addition to the advantages already described, a unique benefit of the series-connected, voltage-controlled architecture is derived from its ability to *Decouple* primary and secondary feeders over a broad range of operating conditions, unlike its shunt-connected counterpart. In particular, the series-connected architecture enables a device's output voltage to be set independently of its input voltage over a large dynamic range. Moreover, this dynamic range is entirely independent of the feeder structure and impedance upstream or downstream of the device. This characteristic has important practical implications on the operation of a feeder network. Loads that are downstream of a series voltage-regulating device can be protected from upstream voltage variations, whether such variations are induced by capacitor bank switching, system sags/swells or variable, large-scale, renewable generation. Also, via this same mechanism, harmonics induced by nonlinear loads located downstream of a series-connected device can be contained from reflection onto the primary feeder, and vice versa. This ability to *Decouple* power quality variations between primary and secondary feeders arises from the highly nonlinear input/output relationship of a series-connected, voltage-controlled architecture. In contrast, shunt-connected, current-controlled architectures exhibit linear input/output relationships, severely limiting their dynamic range, and thus their ability to provide such decoupling.

THE BENEFITS OF **DECOUPLING** ON FEEDER-WIDE STABILITY

A common view today is that a fleet of shunt-connected, current-controlled devices can be used in concert to affect the entire feeder voltage profile. Traditional switched capacitor banks are prime examples of the use of distributed VARs along a feeder for voltage support, albeit utilizing relatively few, high capacity (100+ kVAR) devices. An alternative instantiation of the same idea is the use of solar inverters for injection or absorption of VARs at the extreme edge of the feeder. From a high-level functional perspective, these two embodiments of a distributed VAR solution are identical, if not for differences in their respective response times, step sizes, and device ratings (or, equivalently, the number of independent devices needed). However, of the three differences, the number of independently operating devices is of critical relevance to feeder stability from a control systems perspective.

It is well known to distribution engineers that multiple switched capacitor banks deployed along a distribution feeder can interact adversely unless their corresponding set points (response times,

PERFORMANCE AND STABILITY TRADEOFFS OF CURRENT-CONTROLLED DEVICES

Although system stability can be ensured through proper design of control algorithms for current-controlled devices, there exists an inescapable design trade-off between performance (control accuracy and response time) and feeder-wide stability. On one hand, open-loop control schemes can be adopted that circumvent instability altogether. Indeed, one of the proposed "smart" inverter control schemes, the so-called Q(P) scheme, does exactly this, by varying the reactive power absorbed in proportion to the real power generated by its connected PV system. Note that the use of real power generated as its input, rather than local voltage, averts any feedback loops in the control system because the generated real power is an independent variable determined purely by exogenous factors like solar luminosity, cloud patterns, etc. However, because Q(P) is open-loop, the voltage it converges to is inherently unknown. Worse yet, the amount of reactive power it chooses to absorb can even be counter-productive to the feeder as a whole depending on the states of other "smart" inverters on the system, which, without a robust and scalable communications infrastructure, are unknown.

Alternatively, one can consider a closed-loop scheme that attempts to regulate local voltage to a desired set point, the so-called Q(U) scheme, yet another proposal for "smart" inverter controls. The benefit of the closed-loop scheme is that it attempts to drive local voltage to a known set point, but does so with the potential for system instability resulting from the voltage-referenced feedback paths created amongst the device collective. Generally speaking, one can address these stability issues by extending the response time of each smart inverter and proactively desynchronizing their individual responses, so as to avert collective positive feedback. The result, however, is significantly longer response times (10s of seconds) than the timescales of typical PV voltage variations (seconds), making the performance of closed-loop current control schemes inadequate to address the original problem of local dynamic voltage control. Herein lies the fundamental performance/stability design trade-off that shunt-connected current-controlled devices present.

dead-bands, etc.) are established correctly. The nature of this interaction stems from two fundamental device characteristics: 1) *local knowledge* — each device acts only on local information, without knowledge of the state of other devices on the feeder and 2) *global impact* — the state of each device impacts the voltage at all other devices on the same feeder, irrespective of their location, whether downstream or upstream; a direct result of their shunt-connected architecture. In combination, these two characteristics lead to the presence of *feedback paths* amongst the control systems of each device, resulting in the potential for each device to continually switch in an attempt to find the optimal set point. Distribution engineers will recognize this scenario precisely as the recipe for system instability. With small numbers of current-controlled devices on a feeder (a typical number is 2-3), device placement and corresponding set points can be established, by proper design, to ensure that adverse interactions do not occur. However, when the number of such devices grows to 100s or 1000s, and the physical location and set points of such devices are not under the control of the distribution operator, a scenario currently being proposed with "smart" solar inverters, it is not difficult to anticipate the potential for severe system instability.

THE SERIES-CONNECTED ARCHITECTURE ENABLES OUTPUT VOLTAGE TO BE SET INDEPENDENTLY OF ITS INPUT VOLTAGE OVER A LARGE DYNAMIC RANGE

In stark contrast to shunt-connected devices, *series-connected*, voltage-controlled devices only impact voltage downstream of their location. In particular, when connected on the secondary side of a distribution transformer, they exclusively impact the voltage at the points of common coupling subtended by that particular distribution transformer. In other words, *series-connected*, voltage-controlled devices have exclusively *local impact*, thereby breaking the feedback loops that hamper the performance of shunt-connected control schemes. In summary, *series-connected, voltage-controlled devices are able to decouple primary from secondary and precisely regulate secondary-side voltages independently of, and without impact to, other regulation devices,thereby providing sub-cycle compensation for PV-induced voltage variations while ensuring feeder-wide stability*.

THE IMPORTANCE OF AUTONOMOUS OPERATION

Lastly, it is worth noting that series voltage regulators also present an attractive *operational* advantage over their shunt-connected counterparts. Because series voltage regulators act locally, on local information, and their regulation performance is independent of primary feeder voltage, they can be deployed in a *set-and-forget* mode. At time of deployment (or manufacturing for that matter), their set points can be established (desired output voltage, power factor, and harmonic cancellation range for example), and these set points can further be chosen in the absence of *any* assumption on the associated feeder topology or impedance. Thereafter, they can be relied upon to operate continually and autonomously at those set points. In contrast, current-controlled devices, by the nature of their global impact, require set points to be carefully chosen to avert adverse interactions amongst multiple devices. Furthermore, such set points are a function of feeder topology and impedance, thereby requiring knowledge of the broader deployment configuration. Indeed, should feeder conditions change, their set points may need to be revisited, requiring either recurring deployment of line crews, or communications infrastructure to enable remote management. To summarize, *series voltage regulators can be deployed in the absence of any additional communications or sensing infrastructure. This is not to say that series voltage regulators would not benefit from remote management, as indeed they will, but rather that their associated operational barriers to deployment are very low*.

THE STATE OF EACH SHUNT-CONNECTED DEVICE IMPACTS THE VOLTAGE AT ALL OTHER DEVICES ON THE SAME FEEDER

BUILDING A MULTI-FUNCTION PLATFORM

Although continuous, dynamic voltage regulation is the most critical function required of any power electronics device for the Active Distribution Grid, there are many other power regulation functions (refer to Table 2) that provide significant value to utilities. In particular, power factor correction and current harmonic cancellation are well-served by current-based devices and are not subject to the capacity and coordination limits as in the case of voltage regulation. Consequently, a well-dimensioned combination of series and shunt-connected architectures provides a holistic solution to the challenges utilities face today. Figure 5 shows a simple representation of how these two capabilities might be combined in a multi-function power regulation device, compared with a shunt-only architecture in Figure 6.

***Figure 5* — Shunt/Series-Connected Current and Voltage Source**

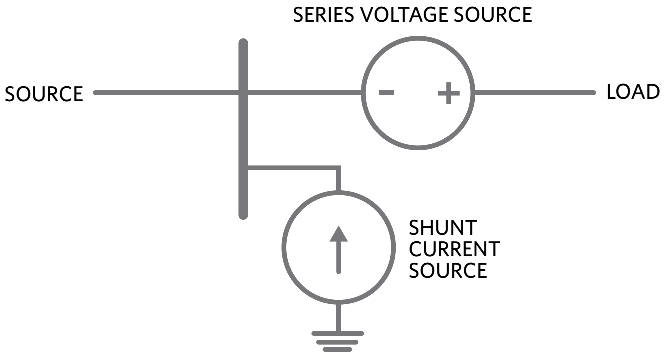
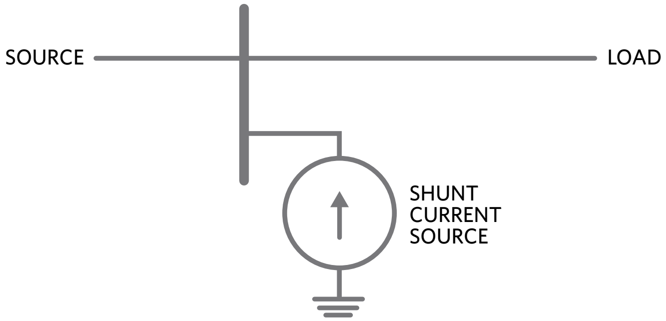


***Figure 6* — Shunt-Only Current Source**



SERIES VOLTAGE REGULATORS CAN BE DEPLOYED IN A SET-AND-FORGET MODE

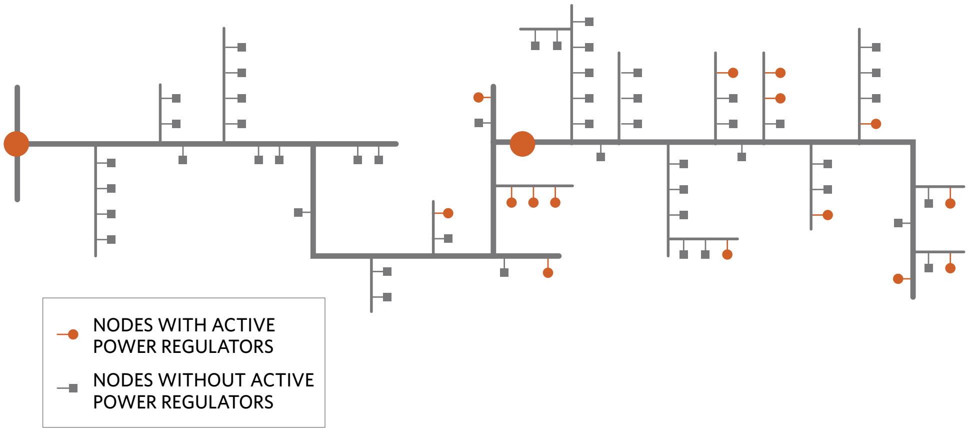
SUMMARY — ESSENTIAL ELEMENTS FOR THE *ACTIVE DISTRIBUTION GRID*

In order for distribution utilities to adapt to an increasingly diverse customer base, from those that are particularly sensitive to power quality deviations to those that resemble small power generation facilities, the power distribution system of today must evolve into the power exchange of tomorrow, one that is adaptive to rapid changes in supply and demand, both spatially and temporally. In such a system, intelligence is necessary, but agility is essential. The *Active Distribution Grid* must be composed of building blocks that are *Distributed, Dynamic,* and *Decoupled* in nature.

Traditional electromechanical power regulation devices have reached the boundaries of their intrinsic capabilities, something that is already evident to those utilities on the forefront of change. Fortunately, however, the recent commercial viability of utility-scale power electronics will enable distribution utilities to address dynamic change where and when it occurs, without requiring them to resort to conventional and costly feeder reinforcement techniques.

Although such advances in power electronics signal the beginning of a new era in utility-scale power distribution solutions, the only solutions that will ultimately prevail are those that exhibit subsidy-free business cases based upon competitive up-front capital costs, recurring operational savings, and low barriers to deployment. Solutions that meet all these requirements mandate the use of hardware platforms based upon a *series-connected, voltage-controlled architecture* at the core, for it is uniquely this multi-function architecture that renders *Distributed, Dynamic,* and *Decoupled* behavior in a cost-effective, efficient, and operationally simple manner. Ancillary functions can be serviced by additional building blocks based on shunt-connected, current-controlled approaches. The intelligent combination of these elements will satisfy the key needs for the *Active Distribution Grid*.

***Figure 7* — Distribution Grid Schematic Featuring Active Power Regulators**



Gridco Systems is singularly focused on developing *Utility-Scale Active Power Regulation Platforms* that enable electric utilities worldwide to further leverage the investments of the past, confront the challenges of the present, and evolve into the power service providers of the future.

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