The Case for DSP Based Volt/VAR Optimization 2012 T&D Conference

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***Abstract* – Using digital signal processing (DSP) techniques as a basis for Volt/VAR optimization (VVO) can provide similar advantages for VVO as they have for system protection relaying, power quality analysis and load forecasting. The use of DSP techniques can overcome many of the obstacles that model based Volt/VAR optimization (VVO) systems face such as the requirement for accurate circuit physical models and the complexity of customer activity which significantly affects loads and makes load modeling even more complex and less dependable. Digital signal processing (DSP) techniques can be used to analyze underlying customer activity and other seemingly random processes occurring on the distribution circuits in real-time and then control based on that analysis in real-time.**

***Index Terms* – CVR, Conservation Voltage Regulation, Conservation Voltage Reduction, DSP, Digital Signal Processing, VVO, Volt/VAR Optimization**

I. Introduction to VVO

Volt/VAR Optimization (VVO) and Conservation Voltage Regulation/Reduction (CVR) have recently gained much attention [1][2]. VVO and CVR are widely recognized as the most economically effective of the many smart grid and Distribution Automation (DA) technologies.

Prior to the advent of the smart grid, the most common way of implementing CVR was with the use of Line Drop Compensation (LDC). LDC is a capability that has been included in most voltage regulator (VR) and on-load tap changer (OLTC) controls for many years. Since the advent of smart grid enabling technologies, mainly the availability of robust communication capabilities with field devices and the development of microprocessors, the term Volt/VAR optimization (VVO) has come into common use. Other terms are also used: VVC (Volt-VAR control), IVVC (Integrated Volt/VAR control) and CVVC (Coordinated Volt/VAR control) are among the most common. VVO is the coordinated operation of voltage regulation devices and switched capacitor banks to achieve utility goals. Those goals may vary from utility to utility, but generally include the minimization of lagging kVARs and controlling distribution voltage levels to some "optimum" point. In some cases, the goal may be to reduce peak demand or to obtain overall energy conservation by implementing CVR. In other cases the goal may be to increase load or even increase lagging kVARs.

In addition to the utilities' "optimum" goals, there are at least three operational constraints that any VVO technology must meet: 1) The voltage provided where the customer is connected to the utility (usually the service entrance) must be within acceptable bounds which are set by ANSI [3] or CSA [4] in the United States and Canada[1]; 2) The VR or OLTC tap changes must be limited to avoid undue wear and premature failure of the tap changer contacts or the tap changer mechanism [5]; and, 3) Capacitor switching must be limited to avoid undue capacitor switch wear and premature failure and also to avoid, in as much as possible, the transients caused by capacitor switching [6].

II. DSP - An Advantageous approach to VVO

Digital signal processing technology (DSP) has been applied widely in many applications such as audio signal processing and compression, digital image processing and video compression, speech processing and speech recognition, digital communications, RADAR, SONAR, seismology and biomedicine. Some specific examples are speech compression and transmission in cellular phones, weather forecasting, economic forecasting, seismic data processing, analysis and control of industrial processes and medical imaging such as CAT scans and MRI. In the arena of power systems engineering, DSP is being used extensively in relaying and system protection [7] and power quality monitoring [8][9]. It is also being considered for use in short-term load forecasting for generation scheduling [10].

Using DSP techniques to extract information about the distribution system as a basis for VVO overcomes the need to use complex physical circuit models (usually geographical information system models) and the difficulty of developing load models that accurately reflect actual distribution circuit loads. DSP based VVO can handle changing load characteristics and physical circuit design changes without the need to change either load models or GIS models [11]. This inherent adaptability will simplify the integration of new loads such as PHEV (plug-in hybrid electric vehicle) and EV (electric vehicle); simplify the addition of distributed generation such as PV (photo-voltaic) on distribution circuits, as well as the addition of technologies like distributed storage.

By extracting information about the behavior of the distribution system, DSP can be used to predict load forward to allow the minimizing of tap-changer and capacitor switching operations, while at the same time providing effective voltage

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[1] Other countries have differing standards.

control and improved performance of VVO systems. DSP facilitates designing the system to recalibrate itself when switching, or when new construction changes the topology of the distribution circuit. Due to the availability of purpose built digital signal processors, the cost of DSP based VVO system computing power will likely be less than the cost of computing power for other VVO systems running on general purpose microprocessor based PCs or server networks.

III. Physical Circuit and Topology Factors Addressed by DSP Based VVO

There are several non-customer activity factors that affect voltage levels on any distribution feeder – two are discussed below. Some factors are deterministic and some are random. Different DSP techniques can be used to address virtually all of them.

A. Physical topology of the distribution feeder circuits

A distribution feeder and its connected loads are an electrical network; albeit a very complex network, even for the simplest of radial distribution feeders. As such it is subject to all of the fundamental electrical principles and laws, such as Ohm's law and Kirchhoff's laws, with the network impedances and nodes depending upon the current topology of the feeder.

The topology of the distribution feeder circuit refers to all physical information about the circuit including connected equipment such as distribution transformers and capacitors and their nameplate ratings, conductor sizes and spacing of all conductors in all branches, laterals and secondary conductors, temporary cuts and jumpers and switch positions.

Topology of the circuit affects the voltage drop in any section of the circuit. The voltage level at one customer delivery point on the distribution feeder is affected by customer load currents in all other sections of the feeder. Likewise the voltage levels at all other customers on the distribution circuit are affected by the load of any one customer on the circuit.

In order for a model based VVO system to operate correctly the physical model must be correct, sometimes a daunting and very labor intensive and costly task. Using DSP on real-time signals collected from the distribution system essentially does away with the need for physical models in VVO control methods.

B. Physical condition of distribution circuit elements

The high resistance caused by any loose or faulty jumpers or connectors on feeder primary circuit conductors will increase voltage drop and affect voltage at many points on the circuit. When they are located on a secondary conductor they will affect at least one customer, and often more. (Not only do loose and faulty jumpers or connectors affect voltages, they have been known to cause fires resulting in millions of dollars of damage.) Faulty distribution circuit elements are not likely to be entered into a physical model and therefore model based VVO cannot take them into account. Here again, DSP techniques provide an answer and also can be used to detect a physical problem and help a utility diagnose and repair it.

IV. Load Modeling Complexities Overcome with DSP Based VVO

DSP based VVO does not require load modeling, as does model based VVO. DSP is used to analyze voltage data and other signals and can actually characterize the load, in some cases forecasting the load forward in the short term.

Load modeling and load characteristics receive a lot of attention because of the effect those characteristics have on transmission system stability. Because of this, there have been substantial efforts to improve load models [12]. The load that the transmission system sees is the same load that is so influenced by customer activity and other factors at the distribution level.

The limitation of model based VVO systems is obvious when all the factors that affect load and voltage on a distribution circuit are taken into account. In 2010, Pacific Northwest National Laboratories (PNNL) performed an evaluation of CVR on a national level [13]. In this evaluation, two of their conclusions, among others, were: 1) "The analysis of CVR, as well as other smart grid technologies, requires the use of time-series simulations," and 2) "The behavior of end use loads is more complicated than generally acknowledged. Voltage dependent multi-state models must be used to accurately represent the effects of CVR." When doing computer based CVR simulation, obtaining an accurate load model is a complex undertaking.

A load model used for VVO control needs to accurately reflect customer activity, changing customer load characteristics and varying load to voltage responses.

A. Customer activity

In general, customer activity can be looked at as the underlying process, or processes, affecting circuit loading, which in turn significantly affects voltage levels at different locations on a distribution feeder circuit. Customer activities generate the actions or conditions which result in specific loads at specific locations turning on or off and even the adjustable level of some of those loads.

Customers are usually classed as residential, commercial or industrial. The following are different types of activities that each class of customers will typically undertake:

1) Residential customer activities

Residential customer activities can be foreseen or predicted in some cases, for example we can predict that a given family will act in certain ways on normal working week-days while the same family will act differently on week-ends or holidays. We also know that certain activities will change seasonally and depend on temperature and other weather conditions. While we can predict in general what they will do, it is not possible to predict with certainty exactly what they will do and when they will do it on any given day. Further, no two customers will act precisely the same, or act at the same time.

2) Commercial customer activities

Commercial customer activities may be able to be predicted more reliably based on time of day and day of the week. However, even with commercial customers, activities may differ with season and special events (ie. a sale at a super market, or school letting out because of snow).

3) Industrial customer activities

Very large industrial customers are usually served by dedicated substations or express feeders. However, smaller industrial customers are likely connected to the same distribution feeders that serve residential and commercial customers. Industrial customer activity generally depends upon the "order book," but can also be affected by other things, such as economic recession, new products being manufactured, or the automation of processes. Industrial loads can vary widely during a work day with shift changes and breaks.

B. Customer load characteristics

Fundamental changes in customer load characteristics occur frequently. For example, electronic ballasted lighting is replacing incandescent lighting, resistive space heating is being replaced by heat pumps and customers are acquiring computers and home electronic devices. Customer loads can be automatically actuated, customer actuated or a combination of both.

1) Residential customer loads

Some examples of residential automated actuated loads would be sump pumps and automatic lighting. Examples of customer actuated loads would be room lighting, computers, television sets, cook stoves, and garage door openers. Examples of loads that are a combination of both would be heating or air conditioning loads, washing machines and dryers, freezer and refrigerator compressor motors and associated fans.

2) Commercial customer loads

Commercial customer loads generally will include HVAC and lighting loads. They will tend to be automatically actuated during certain portions of any particular day. An example would be when the business is open, the lighting is on and the HVAC operates at a particular set point. When the business is closed, only a portion of the lighting would remain on and the HVAC set point would be changed to reduce energy usage. To further complicate matters this reduction could be scheduled at varying times on different days.

3) Industrial customer loads

Industrial customer loads generally are much larger than residential or commercial loads. Usually, induction motor load is the largest part of the industrial load. Induction motors may either operate "across-the-line" or be connected using variable frequency drives. Large DC motors, synchronous motors and process loads which are controlled using feedback are also common.

C. Other customer activity related factors

Weather and climatic conditions, as well as seasons, affect customer behavior and cause changes in load patterns. Distributed Generation (DG), such as home solar panels or photovoltaic (PV), are affected by solar flux. Even clouds passing overhead can reduce the output of the panels - in some cases 90% drops in PV cell output have been seen by Hydro-One personnel in Ontario[2]. As electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) become more common the act of charging them and drawing energy from them during peak periods will become problematic for determining accurate load models. Statistics and probability, which are often closely associated with DSP, will allow a DSP based VVO system to respond properly.

D. Load reaction to voltage

Each type of load and even loads of the same type but of different design or with different motors, will react differently to different voltage levels and changes in voltage levels.

As a simplified example, assume two exactly identical refrigerators set to the same temperature with exactly the same contents and the same ambient temperature, both with compressors and fans running. One refrigerator is operating at Customer 1 near the end of a distribution feeder, and the other is operating at Customer 2 near the substation. Assume Customer 1 and Customer 2 are identical in every way - the customer premises, wiring and all of his other loads are identical and the timing of electric appliances and load turning on and off is the same. Also assume that the substation voltage is lowered 3 volts, and the same 3 volt change occurs throughout the feeder; except that Customer 1 will see a change from 117 volts to 114 volts, and Customer 2 will see a change from 126 volts to 123 volts. Will the change in power input level be the same for both refrigerators? The answer is no, the input power level change will be different [14]. In real life where the two customers are not identical the different load to voltage reaction is accentuated.

V. Other potential DSP based VVO advantages

DSP based VVO systems potentially have other significant advantages. Among them are:

1) Increased tap changer life

DSP based VVO usually directly controls VR and OLTC tap position by sending the VR or OLTC control tap change commands. This is possible because DSP based VVO can detect tap changes or lack thereof even without direct tap position or tap change feedback. DSP based VVO can reduce tap change operations up to 33% [15], reducing wear and maintenance costs while at the same time not increasing capacitor switching operations, all while maintaining the lowest possible average distribution line voltage.

2) Better capacitor operation detection

Capacitor switch or fuse operation can be detected by a DSP based VVO system, even if no direct feedback is available from the capacitor controller.

3) Better CVR and demand reduction performance

DSP based VVO systems can maintain lower overall average voltages because there is no need to build in safety margins on voltage set points in order to account for modeling errors. Therefore DSP based VVO can provide better energy conservation performance and demand reduction.

4) Aggressive Peak shaving

Aggressive peak shaving can be implemented in DSP based VVO systems.

5) Provide system maintenance alerts and diagnostics

DSP based VVO systems can aid in the detection of faulty equipment. Two examples are regulators with open shorting coils and regulators that tend to tap multiple times when a tap change is commanded either by the VVO system or by the

[2] During a discussion the author had with Hydro-One engineers at a conference in Toronto in 2010 they related that in some of their test areas they saw 90% drop in output when clouds passed over.

local VR or OLTC controller[3]. In both cases early detection of these conditions allows timely correction before potential catastrophic failures occur which can result in outages and other damage or injury to both the utility and to the public.

6) Lower requirement for computing power

DSP based VVO systems require much less computing power than model based VVO systems which can require banks of servers. The use of imbedded digital signal processors allows the VVO system to appear more like an intelligent electronic device (IED) or a remote terminal unit (RTU) which can be installed and maintained by utility maintenance and engineering personnel rather than a central computer or server system which requires significant IT and system modeling support, in addition to the aforementioned maintenance and engineering support. Not to mention the saving the energy used for cooling large computer rooms.

VI. Conclusion

There are many complex factors which influence the operation of electric distribution systems which are not easily addressed by traditional (LDC) or smart grid (GIS) model based VVO systems. DSP based VVO control systems can provide better performance with regard to voltage control, CVR and demand reduction. They can reduce a utility's maintenance and operations costs and improve safety. With these complex factors, and the need for robust control systems, DSP based VVO systems will become more prevalent, much as DSP technologies have become more prevalent in other utility and non-utility applications.

VII. References

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VIII. Biography

Tom Wilson (M' 1972, SM' 1985) is a native of Spokane, Washington. After serving in the US Navy as an Electricians Mate, he earned his BSEE from Washington State University in 1971. While working as a Substation Operations Engineer at Pacific Gas and Electric Company, he attended the University of Santa Clara studying MSEE courses. In 1982 he earned his MBA from Gonzaga University. He worked as an Electrical Engineer for Kaiser Aluminum and Chemical Corporation and as an Industrial Control Application Engineer for Reliance Electric. He has also served as a District Engineering Manager for Rockwell Automation and as a Drive Service Center Manager for Omron Electronics.

He is the founder of PCS UtiliData, a Smart Grid solutions provider, specializing in automated Volt/VAR Optimization for utilities and industrial facilities to reduce demand and increase energy efficiency. He holds patents in the U. S. and in Canada for automated voltage control.

A founding member of the Control Systems Integrators Association he has led the company in winning several national and regional awards including the first national CSIA "Charlie Bergman" award, the Rockwell Automation "Circle of Excellence" award" and the IEEE Region VI "Small Business of the Year" award.

He has served on the Western Power Delivery Automation Conference (WPDAC) Program Committee sponsored by Washington State University and also on the Western Energy Institute (WEI) Service Company Committee.

Wilson has been active in the IEEE serving with the Spokane Section in several offices including Section Chair and IAS Chair. During his tenure as IAS Chapter Chair the Spokane Chapter was awarded the Outstanding Small Joint Chapter Award by the IAS. He currently serves on the PES DA Working Group Volt/VAR Task Force.

[3] Both of these actually occurred during a recent VVO project that the author's company was involved with.