Conservation Voltage Reduction (CVR) Technique: A Review

Habibu Hussaini, Abimbola Susan Ajagun, Ashraf Ahmad Adam and Nwozor Obinna Eugene

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*Habibu, H[1], Abimbola, S. A[2], Ashraf, A. A[3], & Nwozor, O. E[4]
[1,2,3,4]Electrical and Electronics Engineering Department, Federal University of Technology, PMB 65 Minna Niger State, Nigeria
*Corresponding author email: habufarid@futminna.edu.ng, +2348066544604

ABSTRACT

The sources of energy to satisfy the demand for energy by consumers are either limited or non-existent depending on the country; as such it becomes necessary to understand ways to better manage the existing power facilities in a prudent manner in order to defer investments in their expansion. This research review seeks to highlight what conservation voltage reduction is about and some of its benefits through extensive and critical literature review. It is desired that this paper will serve as a foundation to those who wants to know about the conservation voltage reduction technique.

Keywords: Benefits, Critical Review, Conservation Voltage Reduction, Energy, Technique.

1 INTRODUCTION

When electricity is being generated the intention is to meet the customers' demand for power. The distribution system delivers electrical energy to the customer at a particular (suitable) supply voltage (Lakervi & Holmes, 1995) from the transmission substations. As the population of the world keeps growing so also is the demand for energy (World Nuclear Association, 2015). The sources of energy to satisfy this demand are either limited or non-existent depending on the country; as such it becomes necessary to manage the existing power facilities in a prudent manner in order to defer investments in their expansion. A technique known as the Conservative Voltage Reduction is used to reduce load demand and conserve energy in the distribution network (Erickson & Gilligan, July 1982) especially during the peak demand period. However, it is important to mention that utility companies have always used the voltage reduction technique as an emergency measure to handle peak demand at critical loading times and to prevent voltage collapse (Hajagos & Danai, May 1998) in the network since the 1960s (Preiss & Warnock, 1978).

The conservative voltage reduction (CVR) is a technique commonly adopted by utility companies to conserve energy through the reduction of the voltage supplied to the loads at the customer's end (Bokhari, et al., June 2014). The loads can be from a residential, commercial or industrial customer (Vaahedi, Fl-Kady, Libaque-Esaine, & Carvalho, November 1987). The main idea behind the technique is the well-known fact that electrical loads consume less power when the supply voltage is reduced. However, the voltage at the customer end is reduced within acceptable limits in order not to damage or impair the functionality of the equipment (Diaz-Aguilo, et al., October 2013). The voltage reduction at the consumer end are commonly limited to about 5% of the nominal rating; this is to ensure that the voltage at the customers' terminal is within ± 10 of its nominal value which is in conformity with the British standard on voltage regulation (Klajn & Bątkiewicz-Pantuła, 2013).

The technique can be implemented through any of the following ways:-line drop compensators, tap-changing transformers, voltage regulators, static VAR compensators, generator excitation control, load control and circuit reconfiguration (Warner & Willoughby, 2013). A factor used to evaluate the effectiveness of the technique is referred to as the Conservative Voltage Reduction factor (CVR_f) and is determined using equation (1) (Sen & Lee, 2014). The quantities are the active power (kW), reactive power (kVar), (real) energy (kWh) and (reactive) energy (kVarh).The CVR_f usually lies between 0 to 2 depending on the load composition.

$$CVR_f = \frac{\%\,Reduction\ of\ Quantities}{\%\,Reduction\ in\ Voltage} \tag{1}$$

2 LITERATURE REVIEW

The United States (US) -based Electric Power Research Institute (EPRI) in the 1980s funded an experimental research to investigate the effects of reduced voltage on the operation and efficiency of electric loads and the outcome was published in (Chen, Shoults, & Fitzer, September 1981) and (Chen, Shoults, Fitzer, & Songster, July 1982). The objectives of the research were to quantify the energy consumption of electric loads in relation to the applied voltage and to provide a way of predicting changes in energy in relation to voltage at circuit level. Different kind of loads were tested at different input voltages ranging from 100/200 V to 126/256 V. The first phase of the research was able to generate all the necessary data required to model the energy consumption of electric loads in relation to applied voltage. The research discovered that the energy consumption for commercial and composite residential loads would reduce by reducing the supply voltage (Kennedy & Fletcher, August 1991). Another achievement of the research is the methodology established for the estimation of energy consumption by loads. Despite the achievements recorded from the research, the results obtained require further field test to validate their accuracy since it is purely experimental. Also, the research was limited to the low voltage level and as a result would require aggregation in order to consider the effects of voltage reduction at higher voltages level (say 33/11 kV). However, Collin et al presented the methodology of obtaining correct aggregate load models at medium voltage level using the residential load sector in UK as an example. The outcome of the research showed that the power network topology has impact on the low voltage aggregate load response to voltage reduction. The outcome of the research can be adapted for analysis of commercial and industrial load sectors not only in the UK but in other countries as well (Collin, Hernando-Gil, Acosta, & Djokic, June 2011).

In (Bokhari, et al., June 2014), the researchers worked on *Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial, and Industrial Loads* and their results were further validated against actual recordings of the change of load to different voltage reduction. The research discovered that the current appliances in residential houses, business premises and industries behave substantially differently than older appliances from about 10 years back. For example, the electronic ballast behaves as a constant power device compared to the magnetic ballast which show a constant current curve. The results obtained in their research tends to be more reliable compared to (Chen, Shoults, Fitzer, & Songster, July 1982) which was purely experimental (without any further field measurements to validate their results) and (Hajagos & Danai, May 1998) which was carried out about 17 years ago after which load composition and behavior to voltage variation has significantly changed (Bokhari, et al., June 2014) as a result of technological advancement. This makes it possible to manufacture better energy saving devices and equipments.

Similarly, Quilumba et al in (Quilumba, Lee, Huang, Wang, & Szabados, October 2011) were able to develop load models for some specific class of next generation appliances such as LED TV, LCD TV and game consoles. The researchers in (Quilumba, Lee, Huang, Wang, & Szabados, October 2011) developed load models for different conditions under each class name such as for LCD TV (black screen, black screen 1080, white screen and white screen 1080), and game consoles (Xbox 360, PS3 and Wii) compared to (Bokhari, et al., June 2014) that developed load models for many equipment under only general class names such as game console, LCD television and so on. Also, both (Bokhari, et al., June 2014) and (Quilumba, Lee, Huang, Wang, & Szabados, October 2011) used different methods to constrain the ZIP coefficients to add to 1 (Lagrange multiplier method in (Quilumba, Lee, Huang, Wang, & Szabados, October 2011) and least square method in (Bokhari, et al., June 2014)), however, the least square method tends to be used more often among researchers to constrain the ZIP coefficient to add to 1 during optimization as in (Schneider & Fuller, July 2010).

In (Lamberti, Dong, Calderaro, & Ochoa, 2013) the research was on *estimating the load response to voltage changes at the UK primary substations*. The ZIP coefficients used to model the load behavior in their work was obtained from the research in (Hajagos & Danai, May 1998) and (Schneider, Tuffner, Fuller, & Singh, July 2010) which were both conducted in the United States. It can therefore be assumed that an appliance operating under the UK voltage system can have the same ZIP coefficients with a similar appliance operating under US voltage system; hence, voltage of operation could be said to have no significant impact on the ZIP coefficients of electrical loads. However, the modelling in (Lamberti, Dong, Calderaro, & Ochoa, 2013) was highly dependent on the time of the day as it does not take into account the varying load characteristics (stochastic nature of loads) with day of week and season or weather which could affect the accurate representation of the load model and applicability or adaptability of the model to different situations. In other words, it means that the model could accurately represent the load during the summer, for example, and be inaccurate during the winter due to the dynamic nature of load and usage. It is important to also mention that sometimes the ZIP coefficients may differ depending on the parameters and conditions considered in the development of the ZIP load models of equipments. For example, the researchers in (Adam, Collin J., 2013) developed and proposed ZIP load models for some lighting and power electronics equipments by including the effects of harmonics among other factors. This makes the proposed load models for such equipments in (Adam, Collin J., 2013) to differ from those reported in the literature (Hajagos & Danai, May 1998), (Louie, 2004) and (Concordia & Ihara, 1982) that did not consider the effects of harmonics on their developed load models for the same equipment.

Bajada et al (2013) modelled household appliances based on the attribute that each device can either be in an ON state or OFF state which is defined by a Markov modulated On-Off process. The model developed was able to adequately represent loads that have two states (that is an active and inactive states). The model also assumes that all activities are not dependent on each other and as a result follow observed arrival rates (Bajada, Fox, & Long, 2013). However, appliances such as washing machines and clothes dryers are some few exceptions to this assumption. This is because the probability of using the dryer just after the washing machine is very high and thus, both appliances can be said to be depending on each other. Additionally, portable electric heaters have multiple heating elements and more than two states. Therefore, this model could be enhanced to accommodate this kind of appliance provided the probabilities of its new state are known. Both (Bajada, Fox, & Long, 2013) and (Lamberti, Dong, Calderaro, & Ochoa, 2013) modelled their loads which basically comprises of household appliances and electrical devices based on the time of the day usage. However, the researchers in (Bajada, Fox, & Long, 2013) used the Gaussian process to handle devices such as electric kettle, washing machine and dishwasher which length of activity is not dependent on time of the day.

Marc et al in (Diaz-Aguilo, et al., October 2013) found that a voltage reduction of up to 4% can be carried out satisfactorily in most part of the New York City network without incurring additional cost in infrastructure from the total 8% voltage reduction applied on the network. This could be because the active and reactive power demands were reduced and the loads functionality is not affected at 4% reduction and also because the voltage drops in the network is within acceptable limits. The researchers in (Diaz-Aguilo, et al., October 2013) modelled the primary feeders and secondary cables of the distribution network as standard pi sections. This is because the pi-section can accurately represent the primary feeders and cables for steady state simulations. The losses in the network are mainly in the cables and transformers. As the voltage is reduced, the flow of current in the network increased and as results increases the series losses (lines and windings losses). On the other hand, loss in transformer cores reduced because it is a function of voltage. The research in (Diaz-Aguilo, et al., October 2013) is similar to that in (Bokhari, et al., June 2014) as they are but further validated by field measurements, however, the researchers in (Diaz-Aguilo, et al., October 2013) did further analyses on losses, voltage violations, voltage distribution, annual energy savings and active/reactive power demand in the network.

In 2013, Sushanta Paul and Ward Jewell researched on (Paul & Jewell, 2013) and discovered that the nature of individual loads either as constant power, constant current or constant impedance have impact on power consumption and line loss during voltage reduction in a network. They developed a model based on the load types and used it to explain the relationship between line loss and voltage reduction. It was discovered that for a composite load system with dominant constant power load and a system with dominant constant impedance load, line loss would increase and decrease respectively in the network. Also, the line loss would increase for a constant current load, if the percentage of constant power load is greater than that with constant impedance load and decrease in the reverse situation. However, there are some exceptions to these rules such as in a situation whereby the resistance of some lines are much higher than others in the same network.

In (Matar, 1990) conservative voltage reduction of 5% was implemented on three distribution circuits with nominal voltage of 12.47 kV. Each of the circuits was designed to have 100% industrial, 100% commercial and 100% residential loads respectively which is similar to the load composition in (Hajagos & Danai, May 1998). It was discovered that after the implementation of the voltage reduction on the network circuits both energy consumption and power demand levels were reduced from the results obtained and the extent of reduction is dependent on the load type, demography, network topology and geographic location same as reported in (Diaz-Aguilo, et al., October 2013). The interesting part of this research (Matar, 1990) is in its ability to quantify the cost benefit of implementing CVR on the power system network. The research did not discussed about the system losses which could show benefits of CVR implementation on power system network in terms of loss reduction.

In (Hajagos & Danai, May 1998) the simulation study was carried out on an area of Ontario Hydro’s system with varying load composition in six zones of the area. Each of the zones in (Hajagos & Danai, May 1998) had varying percentage of load composition from the industrial, commercial and residential load sectors (such as 90% industrial load in zone 4, 63% commercial loads in zone 5 and 42% residential load in zone 2) with none of the zones having 100% load composition from a particular load sector as in (Matar, 1990). This would allow the researchers in (Hajagos & Danai, May 1998) and (Matar, 1990) to determine the effect of voltage reduction on the active and reactive power demands response of loads in each of these load sectors and when they are mixed in varying proportion. According to the literatures (Preiss & Warnock, 1978), (Kirshner & Giorsetto, 1984), (Warnock & Kirkpatrick, 1986), and (Kennedy & Fletcher, August 1991) the highest relative energy saving per percent of voltage reduction was from the commercial load sector (0.85% to 1%), followed by the residential (0.6% to 0.8%) and then the industrial load sector (0.35% to 0.5%). The reason given for the low relative energy saving per percent of voltage reduction recorded in the industrial load sector was due to consistent energy loss during the off peak period which was attributed to the mostly motor load in the sector (Preiss & Warnock, 1978) and also incomplete data set. However, since the percentage reduction in energy with voltage reduction depends on the load type, load composition (or mix), network topology, test duration and climatic condition among other factors, this trend could vary from one study to another and from one utility to another.

3 BENEFITS OF CVR

Some of the benefits of conservative voltage reduction method in power system planning and operation are provided in the following subsections:

3.1 LONGER LIFE SPAN OF NETWORK TRANSFORMERS AND REDUCTION OF STRESS ON THE NETWORK

This is true in the sense that the iron or core losses associated with the transformer are dependent on the impressed voltage; hence a reduced voltage would results in a lower transformer iron loss (Central Station Engineers of the Westinghouse Electric Corporation). This is because the transformer core loss is proportional to the square of the applied voltage (Fuchs, Yildirim, & Grady, 2000), (de Leon & Semlyen, 1995). However, the winding loss is expected to increase with voltage reduction since it is a function of the load current (Chen, Shoults, Fitzer, & Songster, July 1982). This is because as the voltage is reduced the load current increases, although this also depends on the load composition (Paul & Jewell, 2013).

The reduction of power demand by loads as a result of CVR implementation will lead to a reduction in the stress on the power network and can also reduce the possibility of power outages during peak periods.

3.2 ENERGY SAVINGS IN THE NETWORK

A cumulative energy saving in the network would be realized due to the reduction in power demand by loads when the supply voltage is reduced. When considered for a year, the saving in energy is significant up to about 1% (close to 1.3 GWh) for a 1% voltage reduction reported in (Matar, 1990) and about 1.7% (approximately 2,686 GWh) in (Scalley & Kasten, August 1981) for the same 1% reduction in voltage. Similarly, a recent report in 2005 showed a 0.4% (about 1,500 GWh) energy saving per annum for a 1% reduction in voltage (Lefebvre, et al., 20-24 July 2008), while a report prepared for the U.S Department of Energy in 2010 showed a 3.04% energy saving per annum on a national level (Schneider, Tuffner, Fuller, & Singh, July 2010).

Also, an interesting finding is the outcome of the research carried out in Australia where it is concluded that; a 1.05% and 2.28% reduction in real and reactive power respectively could be realized for every 1% reduction in voltage (Pisani, 2011). Finally, a study in (Willard H., June 2006) conducted in the U.S. found that for a 5% reduction in voltage applied across the whole of the distribution network; an energy saving of 2% was realized. Therefore, it can be said that as a "*Rule of thumb*" reducing the voltage supplied to the load by 1% would result in about 1% reduction in active power demand (and energy savings) and at least 1% reduction in reactive power demand by the load (Sen & Lee, 2014), (Scalley & Kasten, August 1981).

The variation in some of the statistics enumerated above in terms of percentage energy savings, active and reactive power reduction reported with percentage voltage reduction from one network or report to another could have resulted from the fact that the percentage reduction of these quantities (energy, active and reactive power) are mostly dependent on the load type and mix in a network (Warner & Willoughby, 2013). Therefore, the variation could be attributed in part to the load composition of circuits tested, nominal voltage of feeders used, time of the day tests were conducted, duration of the voltage reduction test, climate and number of circuits put under test for voltage reduction (Scalley & Kasten, August 1981) which could vary from one network or report to another.

3.3 REDUCTION IN THE CARBON DIOXIDE (CO_2) EMISSION AND COST

The implementation of the CVR technique has been found to help reduce the amount of carbon dioxide emission into the environment and possibly reduce network power generation cost (Pisani, 2011), (Diaz-Aguilo, et al., October 2013). This is because more power generation stations would have been established in order to handle the growing energy demand of customers by the utility companies especially during the peak periods. However, the energy saved using the CVR technique could be used to handle the peak periods demand and as a result defer investment in expanding existing network structures or building new ones which would translate into less CO_2 emission into the environment and less operating cost for the utility companies (Dorrody, 2014). Also, at reduced voltage the consumers save energy and would pay lower bills.

4 CONCLUSION

When the conservation voltage reduction technique is correctly implemented, it leads to energy conservation through reduction in power demand and energy consumption. However, the reduction in energy consumption and power demand is mostly dependent on the load type and mix in a network.

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