



Application of Voltage Deviation Index-Based Optimal Placement of Custom Power Device on Distribution Network

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ABSTRACT

This paper studied the impact of an optimally placed custom power device such as a DVR on a grid-based distribution network. Data for this research was obtained from the DELSITH 1 x 7.5 MVA injection substation which supplies the DELSUTH 11/0.415 kV distribution network. The effect of the DVR on the distribution network has been modelled and studied in the ETAP 16.0 software environment using the voltage deviation index optimal placement technique. The results obtained show that the average real power demand reduced from 5.152 MW to 4.104 MW (21%) and the reactive power demand increased from 3.113 MVAR to 4.630 MVAR (31%). The total real power loss was reduced from 956.7 KW to 707.7 KW (26%). Reactive power loss was reduced from 697.3 kVAR to 413.7 kVAR (40%) and the system power factor increased from an average of 0.8 to 0.95.

ARTICLE INFO

Article History

Received: June, 2021

Received in revised form: July, 2021

Accepted: July, 2021

Published online: September, 2022

KEYWORDS

DVR, DSTATCOM, UPQC, CPD, grid, voltage deviation index

INTRODUCTION

Custom power devices are power electronic controllers, which are mainly deployed in the distribution system for voltage stability and improvement. Custom Power devices are based on the semiconductor switches principle to protect sensitive loads in case of power supply disturbance (Izhwan, Marion, Amran & Radzi, 2007). The most common Custom Power devices employed in the radial distribution network for voltage deviation mitigation are grouped into three kinds; Dynamic Voltage Restorer (DVR), Distribution Static Synchronous (DSTATCOM) and Unify Power Quality Conditioner (UPQC).

Custom power devices (CPDs) are power electronic digital converters that are designed to perform control of various power distribution parameters in lines, both in steady state condition power flow and dynamic stability control (Hamzah, Muhamad & Arsad, 2007). They are capable of improving system voltage profile, and electric power transfer capacity, enhancing electric power system stability, minimising distribution line losses, improving power factor,

etc. With the quick development in the field of power electronics, custom power devices have been recommended for use in the operation, and control of the distribution network (Benachaiba & Ferdi, 2008). They can control the reactive power (Q) flow by controlling the firing delay angles of the thyristors. They can be employed in the transmission and distribution section of the power system for managing the demand for reactive power and voltage profile. Amrita & Nadir (2008) describes the advantages of CPDs to include;

- a. Custom power devices are employed to mitigate power quality problems in distribution by providing voltage stability at the consumer end and regulating energy demand in distribution networks.
- b. They can be optimally positioned for an individual or group of sensitive loads.
- c. Protection of sensitive loads is made easy by the distribution transformer's ability to decrease the short circuit fault on the lower side,
- d. Increase in the energy-carrying capability of the distribution lines to their estimated

thermal limits;

DVR as a power electronics device is used to control its electric reactive power output to regulate profile bus voltages. Compared with mechanically operated switches like capacitor banks, DVR can react fast and has improved

reliability (Boonchiam & Mithulananthan, 2006). The voltage Deviation index can be used for the optimization of various process parameters associated with custom power devices in a power system. A diagram showing the layout of DVR is presented in Figure 1.

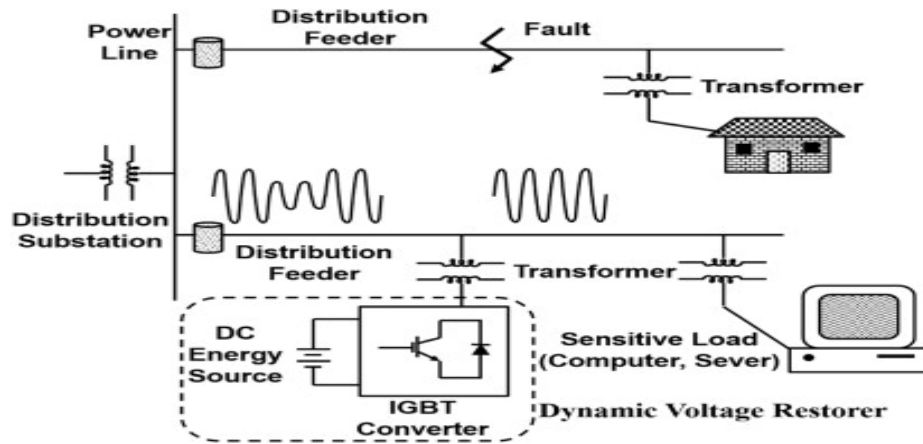


Fig. 1. Block diagram of DVR

As seen in figure 1 the DVR is made of a voltage source inverter, a series voltage injection transformer, an AC filter, a controlling unit, and a storage unit (Filho, Abreu, Arango, & Noronho, 2002). The principle of operation and function of a DVR is to provide sufficient and suitable voltage quality in series with the distribution network using boosting transformer each time there is voltage deviation in the distribution network.

In the secondary distribution system, at some point, the supply voltage V Supply decreases from the standard acceptable value of $\pm 5\%$ of the nominal voltage value. The dynamic voltage restorer will provide a sequential electric potential via the boosting transformer in a way that standard acceptable customer electric potential can be maintained at all times (Kasuni & Perera, 2007).

OPTIMAL PLACEMENT TECHNIQUE OF CUSTOM POWER DEVICE IN DISTRIBUTION NETWORK

The primary objectives are often considered in solving the problem of custom power device location in the distribution network. Power loss mitigation, system Reliability and Voltage stability profile improvement, cost reduction, load balance as well as total harmonics distortion reduction are the main objectives used for optimal placement (Gupta & Kumar, 2018). Also, several factors are considered for equality or inequality constraints of the problem such as power balance, voltage deviation limit, current limit and reactive power compensation. These objectives and constraints are employed by various optimal placement techniques to achieve the desired results.

The optimal placement and sizing of any power device are very important aspects that would maximize the gain of the device integration in a grid system (Igbinke, Sepiribo, Braide & Dikio, 2005). It must be emphasized here that inappropriate or wrong placement of custom power devices in the distribution network can cause serious power quality problems such as



voltage oscillation and loss of investment cost. The impact on total power loss can be achieved by correctly adjusting the position of the device in the distribution system. Ogunboyo, Tiako, & Davidson (2017), list the different methods used in the optimal placement of CPDs in distribution systems including; analytical methods, artificial neural network-based methods, metaheuristic methods, sensitivity approaches, and a combination of various sensitivity index factor approaches.

Analytical Methods: The analytical methods are simple algorithms that have been proposed in the privation of powerful computing resources. The aim of analytical methods in the optimal allocation of custom power devices is to identify the best solutions without considering the nonlinearity and complexity of the problem (Ogunboyo, et. al, 2017). Thus, the major advantage of this method is reducing the computational procedure and some approximations that are applied to the algorithms. The major challenges in applications of an analytical method are loss reduction, improper location and sizes of devices. Even if the location is fixed due to some reasons, the improper size would increase the losses in the system beyond the losses for the case with the device.

Artificial Neural Network-Based Methods: Artificial Neural Networks (ANN) is another suitable method used for modelling online nonlinear systems with many inputs and outputs devices. Some applications of ANN-based approaches in minimizing power quality problems in power systems include; fault detection, voltage control, reactive power control and detection of voltage disturbances (Uhunmwangho, Omorogiwa, & Ofor, 2017). These approaches can find the optimal placement of custom power devices in the distribution network under normal operating or fault conditions.

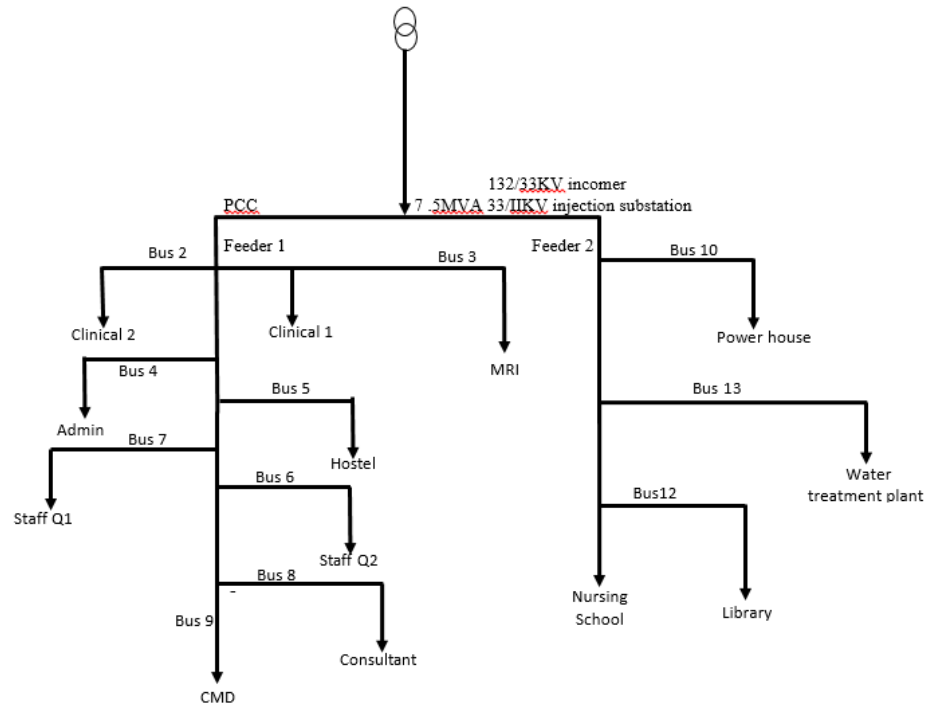
Sensitivity-Based Methods: The sensitivity factor technique is centred on the principle of linearization of the original nonlinear equation around the introductory working point, which assists with diminishing the number of solution spaces. Several factors can be evaluated to set a benchmark suitable for the optimal location of custom power devices in the power system (Vidyasagar, Vijayakumar, Sattianadan & George, 2016). These factors include the voltage sensitivity index, Loss sensitivity factor, voltage performance index, voltage deviation index etc. In most cases, the exact power loss at each bus in the distribution system is determined to ascertain the bus with the highest loss index which can be considered for improvement. The location of the custom power device can be determined by finding any available index factor for different buses to determine the suitable bus that will give the best improvement for the overall performance of the power system. The bus with the highest or lowest value is chosen for the device placement depending on prevailing conditions. In some cases, an algorithm is due to a detection of supply voltage disturbance.

MATERIALS AND METHODS

In this section, the materials used to carry out the research are discussed. Also, the research method used to carry out the research is presented.

Materials

In this study the delta state university teaching hospital, Oghara DELSUTH network is considered for the application of DVR. The network comprises of 1 x 7.5 MVA injection substation transformer with two out-going feeders, and thirteen 11/0.415 KV distribution transformers feeding single and three-phase loads. Figure 2 presents the network diagram.



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Go

Fig. 2. Thirteen bus radial network of DELSUTH power distribution system

Feeder 1 comprises nine 11/0.415 KV distribution transformer substations of different ratings that feeds the main clinical building that houses sensitive loads such as Magnetic Resonance Imaging (MRI), a life support machine in the intensive care unit, and theatre equipment. Feeder 2 has four 11/0.415 KV distribution transformer substations which feed supporting facilities' water, sewage and gas plants.

Data Collection

Data collected includes a developed single-line diagram of DELSUTH 7.5 MVA, 33/11/0.415KV network and various substations rating and distance, as well as copies of their daily log and maintenance book for the facility operational activities. The maintenance log book indicated that one of the important medical diagnostic equipment Magnetic Resonance Imaging [MRI], which is the heart of the hospital, was shut down, without service delivery to patients but the cause was not stated. It was observed

during the site visit that frequent switching operation of 11 KV RMUs's being carried out for load shedding to reduce energy demand affecting electricity price that causes flashover voltage resulting in mal-operation of protection systems and unnecessary interruptions.

The logbook did not contain details of the distribution substations' daily load readings, hence there was a need to visit the thirteen substations at different times of the day to take peak load readings for a period between October 2020 and March 2021. The measurement from each substation was taken with aid of a digital clamp meter match model MS 2001 and digital power clamp meter Fuyi DT-266 which were used in measuring voltage, current, power, frequency and power factor at different times between 10 am and 2 pm for the clinical area, while that of residential area is between 4 pm to 8 pm. The summary of the readings is presented in Table 1.1.



Table 1.1. Daily readings from distribution transformers on DELSUTH 11 kV feeder for October 2020

RATING (kVA)	SUB STATION ID	L ₁	L ₂	L ₃	L _{1n}	L _{2n}	L _{3n}	I _R	I _Y	I _B	P (kW)	Freq (Hz)	P.F	TIME
1000	Clinical 1	378	379	376	220	219	221	502	515	507	577	50.3	0.90	12.10am
500	Clinical 2	375	376	376	218	218	217	400	412	417	416	50.0	0.85	12.30 pm
500	MRI	376	377	375	219	218	219	394	390	391	404	59.3	0.82	11.15am
1000	Power H	386	386	388	222	222	224	450	445	453	610	50.3	0.81	11.00
1000	Admin	380	381	383	220	221	221	550	556	548	573	49.5	0.82	10.30am
500	Library	385	385	384	224	224	226	300	315	320	204	50.0	0.84	10.00
300	Hostel	380	386	380	222	221	220	385	380	380	208	49.8	0.78	7.30 pm
800	Consult	384	382	381	223	220	221	611	616	610	574	50.4	0.88	5.30 pm
500	Nursing	379	378	378	7	116	117	376	376	370	327	49.1	0.81	10.00am
1000	Water	376	374	370	212	216	214	500	568	523	396	50.4	0.86	8.30am
300	Staffs 1	370	371	371	212	210	211	361	363	376	223	9.8	0.80	6.30 pm
300	Staffs 2	369	370	369	215	215	214	360	371	369	347	49.7	0.78	7.00pm
300	CMD lodge	376	376	375	218	220	219	385	399	373	175	50.6	0.81	6.00 pm

Problem Formulation

The objective is to accomplish two goals;

1. Minimize total active power loss, P_i
2. Minimize voltage deviation, V_D.

The distribution power loss minimization is responsible for the redistribution of the reactive power throughout the network, which in turn induces changes in the active power generated by the slack bus. It has been observed that if the network losses were reduced a more uniform voltage profile can be achieved at all the buses of a power system. The real and reactive power losses of the network as modelled in the equation are given by; 1, 2, 3.

$$P_i = \sum_{k=1}^n |Y_{ik}| V_k \cos \theta_k + \theta_{ik} - \theta_i \quad 1$$

$$Q_i = \sum_{k=1}^n |Y_{ik}| V_k \sin \theta_k + \theta_{ik} - \theta_i \quad 2$$

Where P_i = the real power flowing out of bus k, Q_i = the reactive power flowing out of bus k, where, n is the number of distribution lines; Y_k is the impedance of kth bus, V_i < δ_i are the voltages and phase angle at the kth bus. The load bus voltage deviation (V_D) can be expressed by 3.

$$V_D = \sum_{k=1}^{NB} | (V_i - V_r) | \quad 3$$

Where V_k is the voltage at kth bus and V_r is the rated nominal system voltage. The inequality constraints are defined by the following

set of equations; the bus voltage magnitude was constrained within the statutory limit of ±5% given as:

$$V_{\min_k} \leq V_k \leq V_{\max_k}, V_{\min_k} = 0.95 \text{ p.u and } V_{\max_k} = 1.05 \text{ p.u}$$

Also, the discrete values DVR needed were constrained within the commercially available values: Q_c^{min} ≤ Q_c ≤ Q_c^{max}, Q_c^{min} = 1000kVar and Q_c^{max} = 1500kVar

Modeling and Simulation of DELSUTH 11 KV Distribution Network

The simulation is a load flow-based approach using Newton Raphson techniques in an ETAP environment with the installation of DVR for improvement of the network using the Voltage Deviation Index. The following algorithm is adopted to improve the voltage profile of the network.

1. Model the power system in ETAP network simulation soft.
2. Apply the load flow simulation tool, Newton Raphson to study the power flow, voltage profile and Power loss
3. Sizing of DVR using power factor improvement approach
4. Apply voltage deviation index factor for optimal placement of DVR.
5. To predetermine the sensitive buses where DVR is to be located, the VDI for each bus is evaluated voltage deviation index for bus kth

is specified by Eqn. 6 [12]

$$VDI = \sum_{k=1}^{NB} \frac{|V_k|}{V_r} \quad 4$$

Where V_r is the rated desired system voltage, V_k is the available voltage at k^{th} bus and NB is the total number of buses. Buses to be considered for compensation must have VDI less than 1.0 pu so that they can be raised to the statutory limit of $0.95 < |v| < 1.05$ pu

Designed Algorithm for DVR Implementation

The algorithm for DVR device placement using the voltage deviation index (VDI) method can be given as;

1. Obtain the Newton Raphson load flow for the base case.
2. Using equation (4) to calculate the voltage deviation indices for each bus and rank the sensitivities of all nodes to form a priority list.
3. Using equation (3) to size the DVR
4. Pick the bus with the highest VDI and place the value of the sized DVR on that bus.
5. Run load flow to analyse the voltage profile,

voltage deviation magnitude, real and reactive power loss

6. Compare the voltage deviation magnitude with the preceding solution. If the VDI magnitude is more than the preceding previous solution, store this new solution and discard the previous solution.
7. Repeat Steps 4 to Step 6 for all buses in the priority list.
8. Stop.

RESULTS AND DISCUSSION

In this section, we present the results obtained from simulations in ETAP 16.0 network simulation software. These results are subsequently discussed.

Presentation of Results

Figure 3 is a screenshot of the DELSUTH distribution network without the DVR intervention while the simulation of the improved network with DVR intervention is presented in figure 4. The results obtained from the various simulations are presented in table 3.

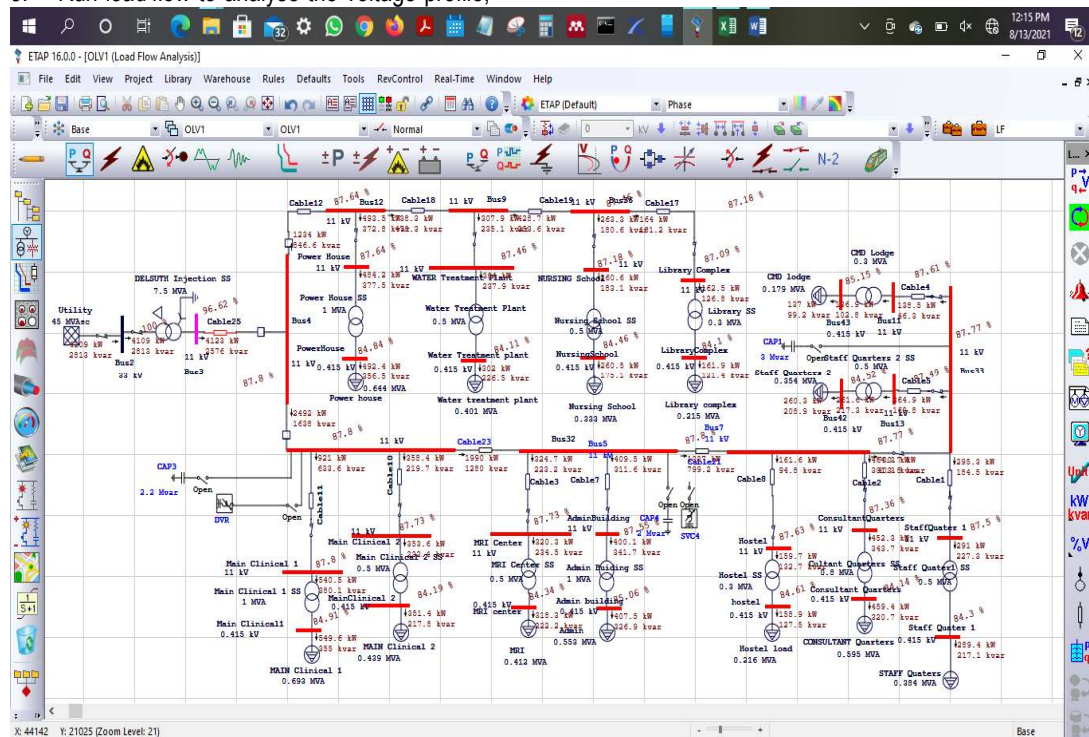


Fig. 3. DELSUTH network without DVR

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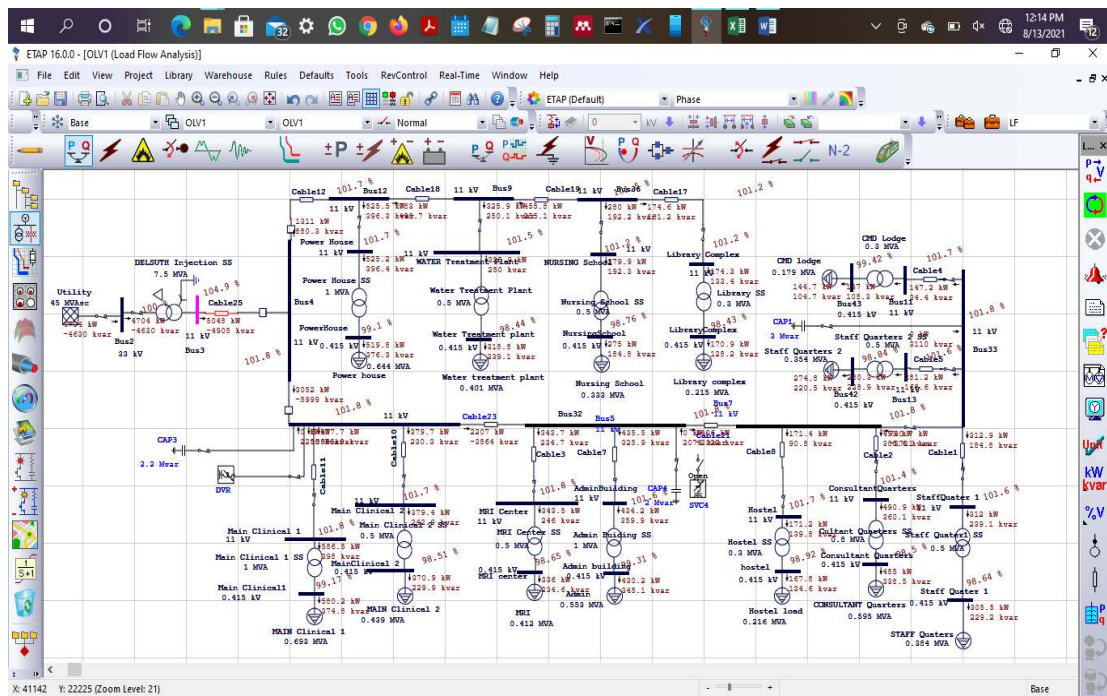


Fig. 4. DELSUTH network with DVR installed

Table 3. Summary of load flow with and without DVR

	Without DVR	With DVR
Power demand MW	5.152	4.704
Power demand MVAR	3.113	4.630
Power demand MVA	6.490	6.600
Real power losses KW	956.7	707.7
Reactive power losses Kvar	697.3	413.7
Network power factor	0.8069	0.9527
No. of buses with under voltage	3	0
The capacity of DVR Kvar	-	1500

DISCUSSION OF RESULTS

The result obtained from load flow analysis of the DELSUTH network shows that the network parameter was enhanced as follows;

1. The load flow analysis carried out on the network shows that out of thirteen 13 load buses 3 had voltage violation which happen to be the buses feeding the main clinical area which consist of mainly sensitive medical equipment loads. However, after compensation, all the load buses' voltage profiles improved and fall within the acceptable limit.
2. Highest voltage deviation occurred at the clinical 1 substation load bus with a VDI of (0.8956).
3. Real power demand reduced from 5.152 MW to 4.104 MW (21%).
4. Reactive power demand increased from 3.113 MVAR to 4.630 MVAR (31%).
5. The total real power loss was reduced from 956.7 KW to 707.7 KW (26%).
6. Reactive power loss reduced from 697.3 KVar to 413.7 KVar (40%).
7. Power in kVA reduced from 6.600 KVA to 6.490 KVA (9%).
8. The system power factor was improved

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from the present 0.80 to 0.95. (15%)

REFERENCES

- Amrita R. A & NADIR A. K., (2008). Modeling & simulation of dynamic voltage restorer (DVR) for enhancing voltage sag. *Sensor & Transducers Journal*, vol. 87, Issue 1, pp. 85-93.
- Benachaiba, C., & Ferd,i B., (2008). Voltage quality improvement using DVR. *Electrical Power Quality and Utilization Journal*, vol.14, no.1.
- Boonchiam, P. & Mithulanathan, N. (2006). Understanding of Dynamic Voltage Restorer, Through MATLAB Simulation. *Thammasat Int. Journal of Science and Technology*, vol.11, no.3.
- Filho, J. M., Abreu, J. P., Arango, H. & Noronho, J. C., (2002) Analysis of power system performance under voltage sag. *Electrical Power System Research*, Elsevier, pp 211-218.
- Gupta, R., & Kumar, A., (2018). Optimal placement of DSTATCOM using sensitivity approaches in mesh distribution system with time-variant load model under load growth, 9 (4) 783-799.
- Hamzah N, Muhamad & Arsad,P.M (2007). Investigation on the effectiveness of dynamic voltage restorer for voltage sag mitigation. *The 5th SCORED*, Malaysia, pp 1-6.
- Igbinake, O., Sepiribo, L., Braide & Dikio (2005). I Improvement of Power Supply at Igbo-Etche Rumoukwurusi, Port-Harcourt, Rivers State using the Dynamic Voltage Restorer (DVR) Method. *Global Journal of Researches in Electrical and Electronics Engineering Double Blind Peer Reviewed International Research Journal*: Global Online ISSN: 2249-4596.
- Izhwan, M. Mariun, M.N and M. Amran M. Radzi, (2007). The effect of power quality on the industries. *The 5th SCORED*, Malaysia, pp. 1-4.
- Kasuni M., & Perera, V., (2007). Control of a dynamic voltage restorer to compensate single phase voltage sags," Master Thesis, Stockholm, Sweden.
- Ogunboyo, P. T., Tiako, R., & Davidson, I. E. (2017), Application of Dynamic Voltage Restorer for power quality improvement in low voltage electrical power distribution network: *An Overview, International Journal of Engineering Research in Africa*, vol. 2.
- Uhunmwangho R., Omorogiuwa E., & Offor E., (2017). Voltage compensation using artificial neural network: a case study of Rumuola distribution network. *Nigerian Journal of Technology*, Vol. 36, No. 1,
- Vidyasagar, S., Vijayakumar, K., Sattianadan, D., & George, F., (2016). Optimal placement of DG based on voltage stability index and voltage deviation index. *Indian Journal of Science and Technology*, 9(38)
DOI:10.17485/ijst/2016/v9i38/101930.