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Optimal Placement of Voltage Compensating Devices in a Smart Distribution Network: The Loss Sensitivity Factor Approach

Joel Osarumwense Egwaile[1], Kingsley Ogbeide[2], A.O. Osahenvemwen[3]

[1, 2] Department of Electrical/Electronic Engineering, University of Benin, Benin City,
Edo State, Nigeria; [3]Department of Electrical/Electronic Engineering, Ambrose Alli University
Ekpoma, Edo State, Nigeria.
Email:[1]joel.egwaile@uniben.edu; [2]kingsley.ogbeide@uniben.edu;
[3]osahenvemwenaustin@ymail.com

Abstract: This paper presents optimal placement of voltage compensating devices in a smart distribution network by deploying the loss sensitivity factor approach. The aim is to improve on voltage profile of the distribution network, and hence mitigate problems associated with poor voltage profiles. The Guinness 15MVA, 33/11kV injection substation and its associated feeders, Benin City was used as a case study. For simplicity, the capacitor is chosen as the compensating device, the method presented in this work can however be adapted for optimal placement of the other compensating devices in a smart distribution network.
Load readings taken from each 11/0.415kV substation and other relevant data collected from the system operator was used to model the network for load flow analysis using the Electrical Transient Analyser (ETAP 7.0) software.
Results show that the network has poor voltage profile, with the highest voltage drop of 14.8% occurring at Ikhueniro 2 feeder, with active and reactive power losses as high as 1.573MW and 5088MVar respectively. The loss sensitivity factor approach was deployed in identifying bus 64 and 44 in the network as the candidate busses for placement of compensating devices, and a rerun of the power flow with compensating devices placed on these busses show that these are indeed the optimal locations for capacitor placement as there was a significant improvement in the voltage profile of the network (from 90.5% to 98.1%) and subsequent reduction in the power losses.

Keywords: Loss sensitivity factor, Compensating Device, voltage profile, Optimal location.

I. INTRODUCTION

Electricity is the most versatile and easily controlled form of energy [1]. Its availability, reliability and affordability are some of the key parameter indicators of a country's industrial growth. This is so because for industries to run smoothly, electrical energy must be readily available and affordable.

The basic mission of an electric power system and its operators is to deliver electrical energy to consumers efficiently, safely and cheaply among other things [2]. Researches have shown that most of the problems resulting in unavailability of electric power supply to customers are traceable to distribution system failures/faults among other things, and in identifying causes of failures in a distribution system; load shedding has the highest impact on feeders particularly in Nigeria. Need for load shedding can be reduced if losses in the network are reduced to the barest minimum. From the design point of view, voltage control measures includes installation of OLTC transformers, AVR installation and power flow optimization among others. [3]

From the operation point of view, measures adopted includes: System voltage control and control on VAR output of the generators, load shedding during under voltage, proper operation of protective devices and their control [4], network reconfiguration [5],[6] etc. Voltage control based on sensitivity analysis are presented in [7], [8]

Another method of reducing losses is for area substation transformers to be spaced 1000 meters apart to prevent excessive voltage drop at the consumer end. [9].

Thus, the aim of this research is to improve on the performance the distribution system in an electric power network by optimal placement of voltage compensating device in the network. For simplicity, this study will focus on optimal placement of capacitors in a smart distribution network using the loss sensitivity approach, it should be noted that the proposed method can be adapted for the placement of other voltage compensating devices (DFacts devices, SVCs etc.) in a distribution network. [10].

A. Reactive Power Control with Switched Shunt Capacitors

Shunt capacitors can be employed in power quality improvement. Research has shown that a good voltage profile can reasonably reduce losses in the distribution feeders [11]. The advantages of this method includes relatively low cost of installation, increase in the transmission capacity of the network, and improved stability of the overall distribution system. However, this would lead to increase in short circuit levels for the uncompensated systems [12]. However, before looking at the how voltage can be controlled in a distribution system by shunt capacitors, let us take a look at the concept of voltage drop in a distribution system.

Figure 1 illustrates the concept of voltage drop in a radial distribution system, while Figure 2 presents the phasor diagram of Fig 1.

The complex apparent power of the load in Fig 1 is given by:

$$S = P_L + jQ_L = U_2 I^* \text{;[13]} \qquad (1)$$

Therefore;

$$I = \frac{P_L - j\,Q_L}{U_2^*} \qquad (2)$$

Where S = Apparent power

P_L = Active Power Drawn by the load

Q_L = Reactive Power Drawn by the Load

U_2^*= Conjugate of the Load Voltage

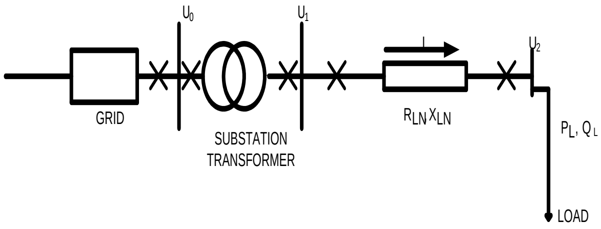

Figure 1: Single line Diagram illustrating the voltage drop in a radial distribution system [14].

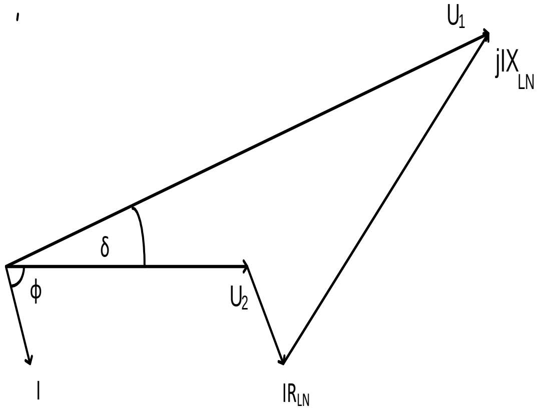

Figure 2: Phasor Diagram for Figure 1

The voltage drop on the feeder connecting bus 1 and bus 2 is given by:

$$|U_1 - U_2| = |I\ (R_{LN} + jX_{LN}| = \left|\frac{(R_{LN}P_L + X_{LN}Q_L) - j(X_{LN}P_L - R_{LN}Q_L)}{U_2}\right| \qquad (3)$$

For a small power flow, the voltage angle δ between U_2 and U_1 in Figure 2 is small,

And equation (3) $\Delta U = |U_1 - U_2|$ can be approximated as:

$$\Delta U = \frac{R_{LN}P_L + X_{LN}Q_L}{U_2} \quad [14] \qquad (4)$$

Equation (4) shows that the current drawn by the load causes a voltage drop on the feeder, and this drop increases toward the load end, hence the need for voltage regulation in a distribution system,

Shunt capacitors inject reactive power to the system whose voltage is to be regulated according to:

$$Q_C = Q_{C,rat}\ U_C^2 \qquad (5)$$

Where

$Q_{C,rat}$ is the Mvar rating of the capacitor,

U_C is the voltage in pu (relative to the capacitor voltage rating).

The reactive power injected into the network by the installed capacitor will compensate the reactive power demanded by the load and thereby improve the voltage profile of the network.

If a capacitor bank is connected to the network of Figure 1, the voltage drop on the feeder decreases to:

$$\Delta U \approx \frac{R_{LN} + X_{LN}(Q_L - Q_C)}{U_2} \qquad (6)$$

If this capacitor bank is adequately able to meet the reactive power demand of the network, the feeder current will also drop to:

$$I = \frac{P_L - j\,(Q_L - Q_C)}{U_2^*} \quad (7)$$

The overall effect is that the power loss in the network will eventually reduce since power loss is a function of the square of current.

To optimize the operation of these capacitor banks in the system, the banks may need to be switched 'ON' at peak loads and Switched 'OFF' at off peak periods to avoid the dangers associated with an overcompensated system. The different control methods of switching these banks include: time, voltage and reactive power controls. The voltage-controlled switching is effective if the banks are to be employed for voltage regulation. However, if the aim is to minimize the flow of reactive power in the network, reactive power-controlled banks are used [15].

II MATERIALS AND METHOD

Here, we present the method/technique, research area and materials used for the study.

A. Loss Sensitivity Factor Analysis

The candidate buses (possible buses for capacitor placement) can be determined using the loss sensitivity factor approach. The loss sensitivity factor gives the rate of change of real power losses in a line as the reactive power on that line changes. This method, helps to reduce the search space during the optimization process.

Consider a distribution feeder k, with line impedance R+jX and a load of P_{eff} + jQ_{eff} connected between bus p and q.
Active power loss in feeder k is given by : $I_k^2 * R_k$ also expressed as:

$$P_{lineloss}[q] = \frac{\left(P_{eff}^2[q] + Q_{eff}^2[q]\right)R_k}{(V[q]^2)} \quad (8)$$

also, the reactive power loss in the feeder k is given by:

$$Q_{lineloss}[q] = \frac{\left(P_{eff}^2[q] + Q_{eff}^2[q]\right)X_k}{(V[q]^2)} \quad (9)$$

Where $P_{eff}[q]$ = Real Power drawn by the load connected to bus "q".
Where $Q_{eff}[q]$ = Reactive Power drawn by the load connected to bus "q".
Differentiating equation (8) and (9) respectively with respect to the reactive power drawn by the load, gives the expression for the loss sensitivity factors in terms of active and reactive power loss as shown in equation (10) and (11).

$$\frac{\partial P_{lineloss}}{\partial Q_{eff}} = \frac{2 * Q_{eff}[q]}{(V[q]^2)} * R_k \quad (10)$$

$$\frac{\partial Q_{lineloss}}{\partial Q_{eff}} = \frac{2 * Q_{eff}[q]}{(V[q]^2)} * X_k \quad (11)$$

The loss sensitivity factor is able to predict which bus will have the highest power loss reduction when a capacitor is placed [10].
Thus, the Loss Sensitivity factors helps to determine the sequence in which buses are to be considered for capacitor placement or other compensating devices as the case may be.
The method described above is adopted for voltage compensation in the Guinness 15MVA injection substation and its associated feeders.

B. Case Study: The Guinness 15 MVA, 33/11 kV Injection Substation Network.

Electric power supply to Benin metropolis is by means of six feeders namely: Etete, GRA, Nekpenekpen, Ikpoba Dam, Siluko Road and Guinness feeders all radiating from the Benin 132/33kv transmission station along Benin-Sapele road, Benin City. Guinness Injection substation is located along the Benin Agbor road, beside the premises of Guinness Nigeria Limited. The injection substation has two (2) outgoing feeders namely: Asaba Road feeder and BDPA feeder. These two feeders has a total of ninety four (94) 11/0.415kV distribution transformers of various ratings connected to it at various points along its length, (i.e. Asaba road 57 transformers, BDPA 37 transformers).

For this network, load readings (real and reactive power, power factor, route length) were measured from all 11kV substations over a period of six months, and average values taken (see samples of measured data in Appendix A). The network was then modelled in Electrical Transient Analyser software (ETAP 7.0) which was used to carry out a load flow analysis (using average load readings measured) with a view to determining the voltage profile on the network under normal condition. Samples of extracts of the load flow result from the ETAP software is presented in Appendix B.

III. RESULTS FROM LOAD FLOW ANALYSIS

The result obtained from load flow analysis of the Guinness 15MVA 33/11kV injection substation and its associated feeders indicate the following:
(a)The load flow analysis carried on the network shows that out of a total of ninety four (94) load buses in the network, voltage violation occurs in all ninety (94) buses

during peak load period, with highest percentage voltage drop (14.8%) occurring at ikhueniro 2 feeder.

(b)Total average active and reactive power loss of the network during peak period is 1.573MW, 5088MVar and 1.337MW, 4.316MVar for peak and off- period respectively.

This high loss in the network is partly due to the poor voltage profile on of the network. Thus there is need to reduce the power losses on the network by improving on the voltage profile of the network.

A. Power Loss Reduction and Voltage Drop Minimization in the Associated Feeders by Application of the Loss Sensitivity Factor.

This method has two parts: in the first part, the loss sensitivity factors calculated from the load flow results is used to determine possible buses for location of compensating devices, and the sequence in which these identified would be considered. In the second part, genetic algorithm embedded in the Optimal Capacitor Placement (OCP) module of the ETAP software is used to determine the sizes of the banks to be located in the bus(es) identified using the loss sensitivity factors.

B. Determining Candidate Buses for Capacitor Placement from Loss Sensitivity Factor.

As stated in equation (10), the loss sensitivity factor is given by:

$$\frac{\partial P_{loss}}{\partial Q} = \frac{2QR}{V^2} = \varphi \qquad (11)$$

Referring to the load flow report nine buses (11 kV) are identified as prospective candidate buses. These buses were chosen due to their location, reactive power drawn, voltage magnitude and distance from the injection substation. These are bus 26, 44, 53, 64, 77, 80, 104, 121 and bus 123.

To determine the order in which they are to be considered as candidate buses we proceed to calculate their loss sensitivity factor from equation (11). All parameters used in the calculation were extracted from the load flow report.

(a) **bus 26:**

Q = 2. 94 MVar, R = 0.62172315, V (pu) = 0.9

$$\varphi = \frac{2.94\ X\ 2\ X\ \ 0.62172315}{0.9^2} = 4.51$$

Going through the same procedure, the loss sensitivity factors for other buses were calculated and the result is as presented in Table 1.

Table 1: Table of Loss Sensitivity Factors.

S/N	Bus No	Total Route Resist(Ω	Q_{drawn} **(MVar)**	Volt Mag	Loss Sensitivity factor
1	26	0.6217	2.94	0.90	4.5132495
2	44	0.6997	2.52	0.89	4.4523498
3	53	0.7216	2.31	0.89	4.2093063
4	64	0.9069	2.12	0.88	4.9659268
5	77	1.0386	0.34	0.88	0.9120319
6	80	1.0288	1.49	0.88	3.9593166
7	104	1.0825	0.91	0.87	2.6029913
8	121	1.7408	0.54	0.86	2.5420373
9	123	2.0236	0.33	0.86	1.8058513

Table 2: Buses arranged in order of priority for selection.

S/N	Bus Number	Loss sensitivity factor
1	64	4.9659268
2	44	4.4523498
3	26	4.3290353
4	53	4.2093063
5	80	3.9593166
6	104	2.6029913
7	121	2.5420373
8	123	1.8058513
9	77	0.9120319

The capacitor banks are to be placed in the candidate buses which will be considered in the order of decreasing loss sensitivity factors presented in Table 2.

C. Discussion

Table 2 shows the bus 64 is the first bus to be considered for capacitor placement; followed by bus 44, 26, 53, 80 etc. until the voltage profile requirement of the network is satisfied.

Having determined the right amount of reactive power to be injected at these locations, a rerun of the power flow was carried out on the network, and the following deductions were made from the result of the power flow analysis:

(a) The best locations for capacitor placement is at bus 64 and bus 44, other location would require larger sizes of capacitor banks, and more candidate buses.

(b) All voltages at the load buses are within acceptable limits for both peak and off peak periods.

(c) Total average active and reactive power loss of the improved system during peak period is 0.1722 MW, 0.4822 MVar and 0.2807 MW, 0.745 MVar for peak and off- period respectively.

(d) The real power losses have been reduced by 89.1 % and the reactive power losses has been reduced by 90.5 % during peak periods.

(e) The voltage magnitude at the candidate buses (bus 64 and bus 44) has been increased from 88.01 % (peak period) and 89.8 % (off peak period) to 97.5 % and 96.75 % respectively.

IV. CONCLUSION

The suggested capacitor banks in the proposed network at bus 64 (T-off after MTN base station along Benin Agbor Road) and at bus 44 (lyobosa Street junction along Benin Agbor road) should have step switching arrangement of 400 KVar summing up to 6000 KVar for peak period and 3600 KVar for off peak period.

By application of the loss sensitivity factor, we have used an method, which is computationally efficient to correct the problem of voltage violation and reduce power losses to the barest minimum in the entire network, by injecting reactive power only at two carefully selected candidate buses.

REFERENCES

[1] International Electrotechnical Commission (IEC) 2013. Energy Efficiency Bulletin www.iec.ch.com. Visited 04/08/2012

[2] North American Electricity Reliability Cooperation (NAERC) mission statement, 2012. Pp 1

[3] H.Vu, P.Pruvot, C. Launay, Y. Harmand,"An improved voltage control on Large-Scale Power system",IEEE Transactions on Power Systems, Vol.11, No.3, August 1996.

[4] S. D. Naik, M.K. Khedkar and S. S. Bhat, " Improvement of voltage stability by OLTC and shunt compensation in large multibus power system", proceedings of ICIEA, pp. 264-269, July 2012

[5] Y . Ch, S.K. Goswami and D. Chatterjee: " Effect of network reconfiguration on power quality of distribution system", International Journal of Electrical Power&Energy Systems,Vol.83,pp.87-95 (2016).

[6] H. W. Li, W. J. Mao, A. A. Zhang and C. Li: "An improved distribution network reconfiguration method based on minimun spanning tree algorithm and heuristic rules", International Journal of Electrical Power&Energy Systems, Vol. 82, No.11, PP466-473 (2016).

[7] S. D. Naik, M.K. Khedkar and S. S. Bhat, " Improvement of voltage stability by OLTC and shunt compensation in large multibus power system", proceedings of ICIEA, pp. 264-269, July 2012 P.R.Bijwe, D. P. Kothari, J. Nanda and K. S. Lingamurthy, "Optimal voltage control using a constant sensitivity matrix",Electric Power Systems Research, 11, pp 195-203, 1986.

[8] M. R. Aghamohammadi, S. Hashemi and M. S. Ghazizadeh," A novel approach for improving voltage stability margin by sensitivity analysis of neural network", Proceedings of IPEC, pp. 280-286, October 2010

[9] F.O.Usifoh S. Omoruyi, F. Igbinovia, P.O.Otasowie " Electrical Power Sector Energy Reform Prospects in Nigeria. Journal of Mathematics and Technology, Vol 5, .2014No 2. pp 5-8

[10] J.O.Egwaile ,F.O. Osayamen "Microprocessor Controlled Capacitor Bank Switching System for Smart Distribution System. Nigerian Journal of Technology,(NIJOTECH) Vol 33, Number 3. pp 318-323 2014

[11] B.Gustavo, K. Bogdan, W. Craig W. "Shunt Capacitor Bank Fundamentals and Protection" Conference for Protective Relay Engineers - Texas A&M University April 8-10, College Station (TX) 2003.

[12] J.C.Whitaker Ed " Ac Power Handbook, Crc Press LLC, U.S.A. ISBN 11. 946 532, 2nd Edition, 1999 PP 25-36.

[13] J.D. Glover, M.S Sarma, T.J. Overbye, "Power System Analysis and Design" H.Jame and H.Gowans Eds, U.S.A, Chris Carson Pub, Fourth Edition, 2008 pp 305-309.

[14] Mithulananthan, N. Salama, M.A. Canlzares, C.A. Reeve, J.(2009) "Distribution system voltage regulation and var compensation for different static load models. International Journal of Electrical Engineering Education 37/4.

[15] T.A Short ed, Electric Power Distribution Handbook, L. L. Grigsby Ed, CRC Press LLC, U.S.A, ISBN 1246 532, 2nd Edition, 2004. PP 125-136.

[16] S.Kartikeya, R Mahammed " Optimal Selection of Capacitors for Radial Distribution Systems Using Plant Growth Simulation Algorithm" International Journal of Advanced Science and Technology Vol. 30, pp 43-52 2011

APPENDIX A

Table 3: Samples of Substation Parameters Used for the Load Flow Analysis; (BDPA Feeder

					AVE LOAD (PEAK PERIOD)		AVE LOAD (OFF PEAK)	
S/N	**NAME OF SUBSTATION**	**RATING (KVA)**	**Route Length (km)**	**Load Power Factor**	**P(KW)**	**S(KVA)**	**P(KW)**	**S(KVA)**
1	AIRHUNWUNDE	300	3.073	0.852	181.578	213.120	121.657	142.790
2	EVBADOLOYI	300	3.028	0.745	130.524	175.200	87.451	117.384
3	IHASE	500	2.893	0.764	71.327	93.360	47.789	62.551
4	ASOWATA	315	2.713	0.643	74.537	115.920	49.939	77.666
5	OSASUMWEN	200	3.793	0.763	67.388	88.320	45.150	59.174
6	ALAGHODARO	300	3.433	0.876	74.215	84.720	49.724	56.762
7	IFASUYI	300	2.308	0.854	117.852	138.000	78.961	92.460

APPENDIX B:Sample of Load Flow Report (Extracts)

Contract: **ETAP**

Date: 03-02-2015
Revision: Base
ConFigure : Normal

Bus		**Voltage**		**Generation**		**Load**		**Load Flow**					**XFMR**
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	% PF	% Tap
Bus9	0.415	87.040	-3.7	0	0	0.019	0.020	Bus7	-0.019	-0.020	43.6	69.5	
Bus10	11.000	92.229	-2.8	0	0	0	0	Bus5	0.000	0.000	0.0	0.0	
Bus11	11.000	85.712	-3.8	0	0	0	0	Bus121	-0.076	-0.043	5.4	87.1	
								ikhueniro 2 fdr	0.076	0.043	5.4	87.1	
Bus12	11.000	90.557	-3.1	0	0	0	0	Bus5	-3.836	-3.197	289.4	76.8	
								Bus14	3.817	3.186	288.2	76.8	
								helius tower fdr	0.018	0.011	1.2	86.0	
Bus14	11.000	90.395	-3.1	0	0	0	0	Bus12	-3.812	-3.179	288.2	76.8	
								Bus16	3.792	3.161	286.6	76.8	
								zenith 1 fdr	0.020	0.018	1.5	74.3	
Bus16	11.000	90.153	-3.1	0	0	0	0	Bus14	-3.784	-3.150	286.6	76.9	
								Bus18	0.097	0.076	7.2	78.5	
								Bus20	0.076	0.043	5.1	87.4	
								Bus129	3.591	3.014	272.9	76.6	
								gt fdr	0.020	0.017	1.5	76.1	
Bus18	11.000	90.143	-3.1					Bus16	-0.097	-0.076	7.2	78.5	

Appendix C. Snap Shot of the Etap 7.0 user interface.

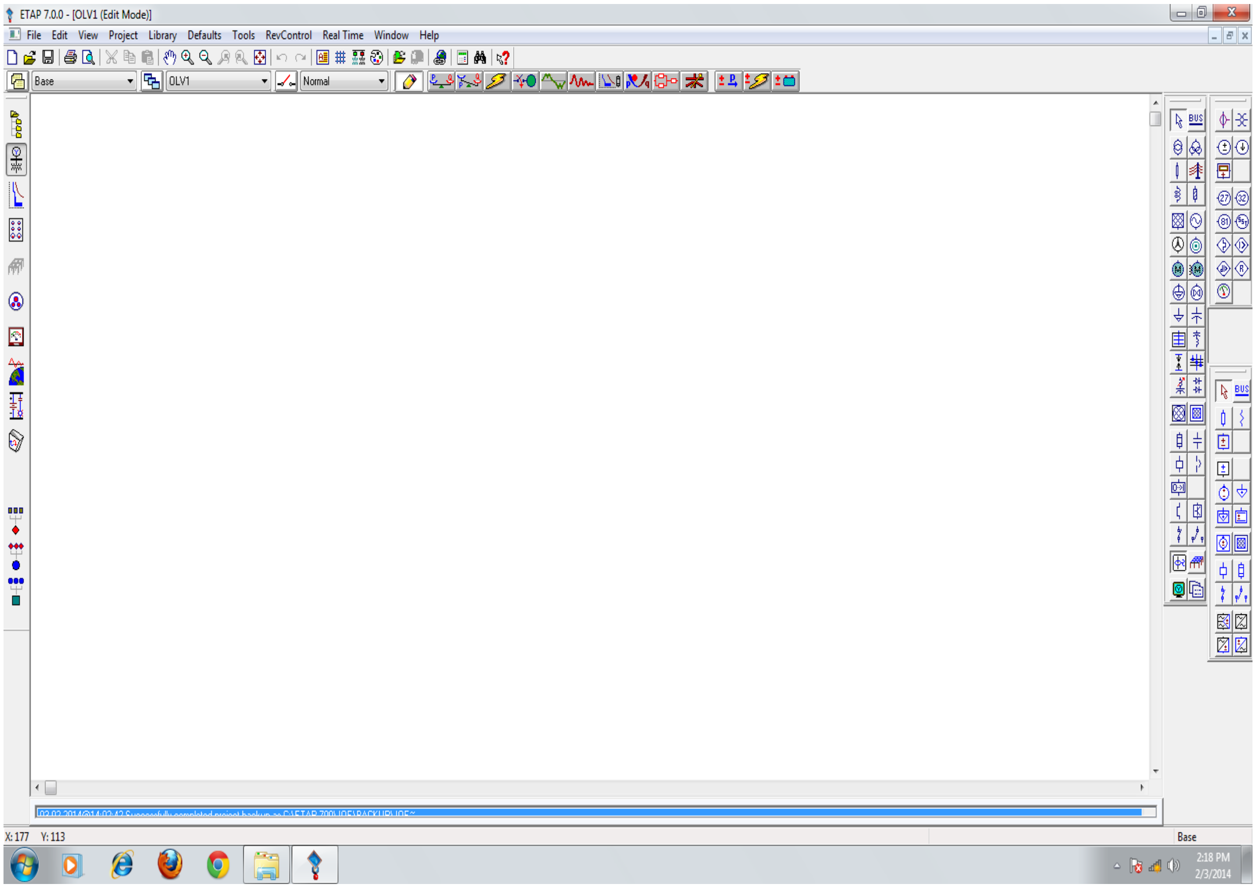

Figure 3 : ETAP 7.0 User Interface.