ACTIVE NETWORKS: DEMAND SIDE MANAGEMENT & VOLTAGE CONTROL

A thesis submitted in partial fulfilment for the requirement of degree in

Master of Science in Energy Systems and the Environment

By

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Copyright Declaration

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Abstract

Electricity distribution networks have been supplying power to customers with very few changes in configuration and operation methods. In the recent years however, due to the addition of local generation on the power distribution system, the network configuration and operation has changed significantly leading to a new concept called active networks. Operation of a simple ring type active distribution network is studied in this project with emphasis on demand side management and active voltage control in view of possible energy conservation and related environmental benefits. A usual mix of loads is assumed on the ring main. A controller is programmed and implemented to execute load switching based on predictions of load curves and embedded generation profiles. In addition, a voltage control program by on-load tap change control of the primary distribution transformer is implemented. Simulations are carried out on a real time digital simulator (RTDS) to study the network performance with the controller. Results are analysed to discuss the various issues regarding active network management (ANM) in context of the overall energy consumption, savings and the related environmental issues. Some issues with power generation companies, distribution network operators (DNO) and the customers with regard to ANM are also observed.

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List of Abbreviations

ANM	Active Network Management
CHP	Combined Heat and Power
DEFRA	Department of Environment Food and Rural Affairs
DG	Distributed Generation
DNO	Distribution Network Operator
DSM	Demand Side Management
GHG	Green House Gas
PLC	Programmable Logic Controller
RTDS	Real Time Digital Simulator
SCADA	Supervisory Control And Data Acquisition

Chapter 1: Introduction

Electrical energy is regarded as high grade energy and has been the major driver for technological and economic development. It is evident that the available power generation sources are inadequate to supply the existing energy demand. In addition, the growing energy needs are widening the gap between the supply and demand constantly.

Distributed Generation (DG) or embedded generation is the new wave in the energy industry which promises to supply for the growing energy demand to some extent. DG is being implemented by integrating renewable energy sources and cogeneration into the existing power system. Also has the advantage of reduced environmental damage due to absence or reduced green house gas (GHG) emissions. However there are many technological and socio-economic issues to be dealt in order to implement DG on a larger scale.

Demand Side Management (DSM) is another option which is equally important and beneficial as that of distributed generation in improving the energy scenario. It is observed that, by inclusion of new energy sources we are only supplying the increasing demand, while an inherent deficit prevails. Therefore, on the demand side, more efficient ways of utilization of the available energy has to be employed. Some measures already in place include load control and/or load shifting by utility companies in order to obtain a better and profitable load curve. In times to come, the possibility of practising DSM in real time is being studied and also implemented on pilot basis by some Electrical Utility companies. By introducing Smart Metering at load centres and intelligent devices for real time control, it is possible to monitor and control the energy demand more economically, increase profitability and also conserve energy.

Connection of DG and introducing schemes like DSM in the distribution system would calls for improved control, automation and protection systems. Automation of distribution network operations can be beneficial in maintaining nominal operating conditions and offer supply security and protection, in the ever changing network configuration of the present day distribution system. The concept of Active Network Management (ANM) is being studied in this regard. ANM applies distribution automation to control network parameters for better operation with DG. For example, allow more connections of energy sources on the network by active voltage control methods. Demand side management could also be part of ANM for load control and hence better energy conservation and consequent environmental benefits.

1.1 Project Aim

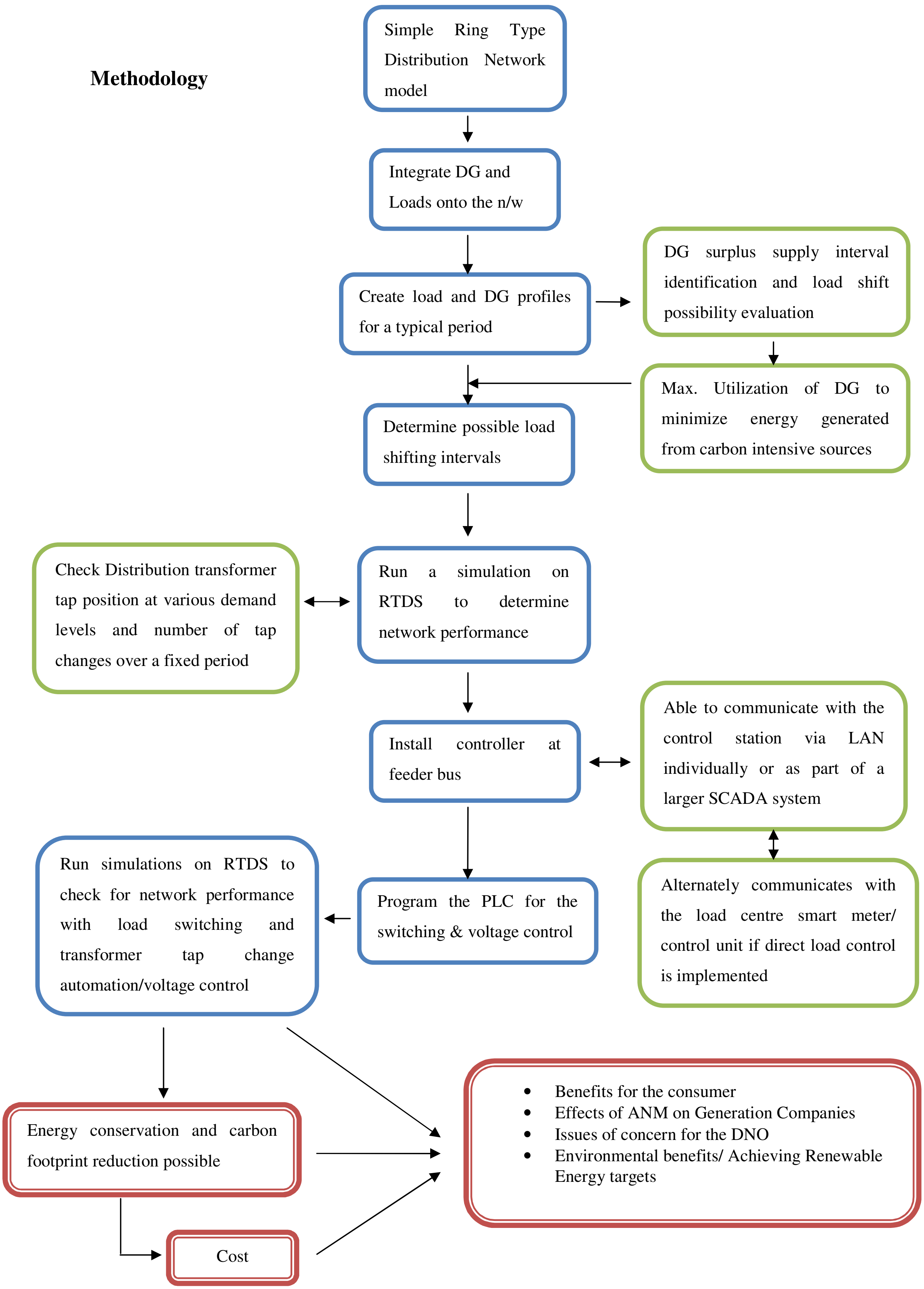
The aim of this project is to study the real time performance of Active Networks with DSM and active voltage control as two cases and evaluate the possible energy conservation as a result of these schemes.

1.2 Project Objectives

The specific objectives of the project are:

- Prepare demand profiles for the loads and generation profiles for DG on a typical ring type distribution network.
- Study the possibility of load shifting and the possibility of maximum utilization of renewable energy/ less carbon intensive sources to supply the loads.
- Control system design using a Programmable Logic Controller (PLC) for Load switching, transformer tap change control and monitoring.
- Study the issues regarding real time DSM and voltage control by conducting simulations of the ring network on the Real Time Digital Simulator (RTDS).
- Analysing simulation results and evaluating energy conservation achievable by this network management scheme.
- Implications of ANM on Generation companies, DNOs and consumers.
- Environmental implications of ANM.

Methodology



1.3 Thesis Organisation

Following the introduction, Chapter 2 gives the necessary background information about Electricity supply system, DSM, DG, Distribution automation and an overview of voltage control using transformer tap change mechanism. Some of the issues noted by previous studies in this area are also mentioned in this chapter.

Chapter 3 details the concept of Active Networks and control of active networks with emphasis on active voltage control.

Chapter 4 gives the details about the example network model used for the study. Load models and demand profiles, DG types chosen and their supply profiles.

Chapter 5 explains the controller selection and PLC programming. Control algorithm design and implementation for the load switching and tap change control tasks.

Chapter 6 gives an overview of the real time simulator (RTDS) and the software program (RSCAD) used to conduct the simulations. The assumptions made and considerations for simulation are explained in this section.

Chapter 7 presents some of the selected results of the simulations with brief analysis of the same.

Chapter 8 opens up a discussion based on the results of the simulations and also the lessons learnt during this project. The conclusions give a closing statement along with scope for future work in the area with some specific suggestions.

Chapter 2: Project Background

The following concepts give the necessary information to better understand the objectives, implementation methodology and results of the project. Important discussions and conclusions of some previous studies conducted in related issues are also included in this section to create a perspective for the project topic.

2.1 UK Electrical System Configuration

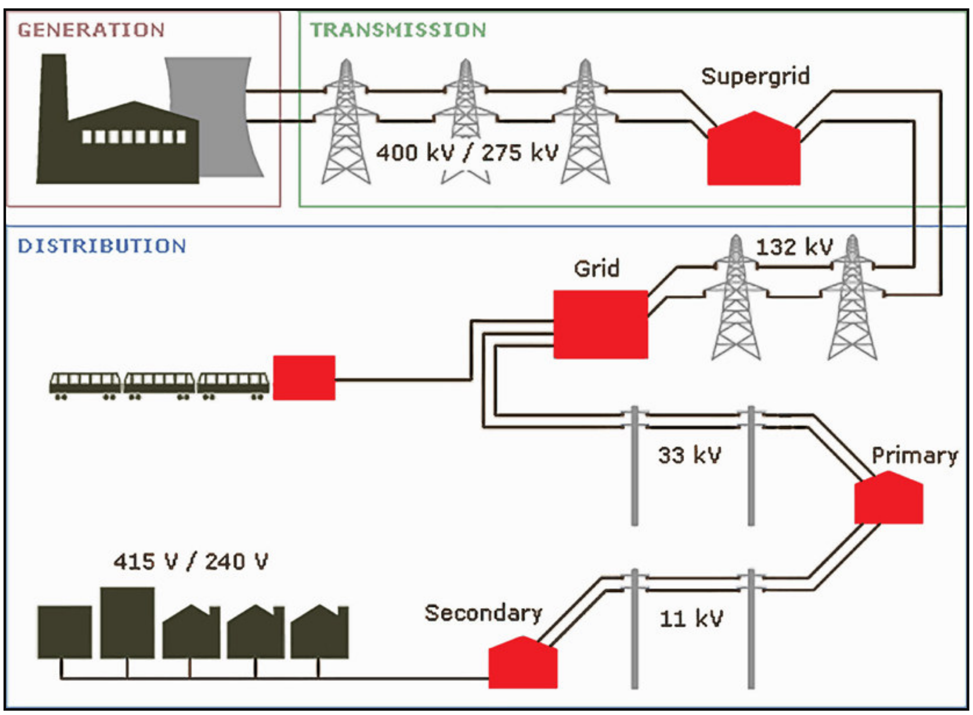


Figure 1: UK Electricity System Configuration [2]

The operating voltages in the supply system vary in different countries depending on generation facilities, transmission distance, and terrain and sometimes for historical reasons as well. The UK voltage levels are as shown above in Figure 1. Typical generation voltage is in the range of 11 to 15kV which is then stepped up to higher voltages before transmission. The Super grid transmits power at voltage levels of 275 to 400kV (EHV). Further substations step down the voltage to 132kV (HV) for transmission. In the grid stations, the voltage is further stepped down to 33kV (MV) which feed the primary substations. The distribution network which follows is branched out from these primary substations at 11kV feeding large consumer loads like industries and secondary substations. From here the 400V (LV) lines emerge out to supply electrical energy to individual customers.

The environmental issues like compliance to the Kyoto protocol, is a major concern for the world and thus remedial measures are being developed to reduce green house gas (GHG) emissions and the carbon footprint. In view of addressing the issues of global climate change and the environmental protocol, the UK has setup ambitious targets for the next few years. In the power sector, the UK government aims to achieve 505 of the nation's electricity generated from renewable energy sources. As a result, cogeneration and small scale renewable energy generation has been the prime focus in the power sector in recent times. Distributed generation poses problems in network operating issues like voltage quality, protection and ultimately supply security.

The increasing demand on distribution networks and the distributed generation on them affect the performance of the network immensely. This has forced utility companies or Distribution Network Operators (DNO) to take up network reconfiguration tasks to improve the current carrying capacity of networks, protection arrangements and also install new substations to cope with the increasing demand.

The power line which supplies energy to secondary substations is called a feeder. Many such feeders supply power to the broad spread of customer locations. There is a limit on the loads fed by a single feeder depending on the current carrying capacity of the conductor (either an overhead conductor or an underground cable). Thermal loading capability of the feeder is also considered to specify maximum safe limit. Therefore, as and when there is an addition of load on the network, new feeders are installed to supply the loads. This calls for new secondary substations being installed and hence huge investments from the DNOs. New infrastructure addition, although not completely avoidable, but it certainly can be postponed.

In the UK, OFGEM, the regulatory authority and private DNOs are conducting in-house research and also funding research projects from private bodies and universities to find solutions to the problems that exist in power distribution. Automating the distribution system and introducing real time control on loads and DG and the associated issues are being studied.

2.2 Demand Side Management

The control of loads in order to achieve a better overall network performance and to obtain a better match between the available supply and the consumer demand can be termed as Demand side management.

"DSM includes all measures, programs, equipments and activities that are directed towards improving efficiency and cost effectiveness of energy usage on the customer side of the meter." [7]

Primary reasons for implementing DSM [5]:

- Shortage of Supply (primarily peak load supply).
- Distribution network overload during peak loads.
- For the utility companies, it is mainly due to uncertainty in future demands, fuel prices and availability. Also to maintain market position against competitors.

Over the years, implementation of DSM has proved to be advantageous to both consumers and the utilities. Some studies in DSM have listed the following points [4, 5, and 6]:

For the consumer:

- Delay in the next price rise for electricity.
- Efficient operation of equipment and hence reduced overall energy bills.
- Chance to participate in the planning stages of a new DSM scheme of a Network Management Programme of the Utility Company; not just as a consumer but as a stakeholder.

For the utility companies:

- Improved load factor (difference between the peak and valley loads on the load curve)
- Building of new generation units and hence setting up associated transmission, distribution networks or reconfiguring the existing infrastructure is delayed. This is an economic option and also reduces the pollution levels.
- The utility can design load curves such that loads perform efficiently and also the network is not overloaded at peak demand intervals. Hence preventing deterioration of network infrastructure and frequent maintenance.

Distribution network operators (DNO) have to maintain network security in order to maintain the patronage of customers and earn revenues to be in business. Therefore, if the DNO is planning to control the usage patterns of their consumers, then they have to undertake feasibility studies and discussions with consumer groups in order to chart out a plan for DSM implementation. Load survey or audits are necessary to determine the usage patterns and thus decide on the control pattern which is to be implemented. DSM can be implemented under an already existing network maintenance or management program to do it in an organised manner. For a utility which is planning to introduce DSM in its network management programme, the following primary questions have to be answered [4]:

- How often is the customer going to be controlled?
- What appliances is the utility going to control?
- What is the power consumption of these appliances?
- How will the utility protect these appliances on the tripping and closing phases of the control time?

Another important point to be considered is that DSM or load management is more effective in reducing the magnitude of capacity deficiency events than in reducing the number of hours during which capacity deficiencies prevail [6].

DSM can be implemented in different stages and sub divided into different programs for ease of operation. In competitive market environment, the DNO has to take care of issues like keeping the consumer/stakeholder informed about the procedures and also secure their market share by promoting themselves to new consumers. Utility programs for DSM could be a combination of the following:

a. Load management
b. Identification and promotion of new users
c. Strategic conservation
d. Load retention
e. Customer generation
f. Adjustments in market share

There is a need to asses which DSM programs/alternatives are better for a given utility network and is not a trivial task given the numerous DSM options. Utilities can develop a ranking of the available DSM options suitable for their load shape objectives after conducting feasibility studies on each and implement them accordingly [6].

The second most important phase of DSM is the Operational or Load shape objectives. The generic load shape objectives are:

a. Peak clipping

b. Valley filling

c. Load shifting

d. Strategic conservation

e. Strategic load growth

f. Flexible load shape

Besides all the advantages of DSM implementation, utility companies would be concerned about some of the following issues while actively implementing DSM measures.

- Large investments for installing DSM equipment and controls may diminish the chance of expanding the fixed assets of the utility itself and slow or no repayment for their investments.
- On the common condition of supplying power the utility may gain less marketing power income because of carrying out DSM so as to affect their profits.

If in any case utilities are reluctant to implement DSM measures in view of the above few reasons which are not highlighting when compared to the advantages of DSM, the Government should formulate encouraging policies to take care of this. A relative structure, not only permit but also prize the power company to carry out those DSM measures proved to have good cost profit by using the own fund and money raised from various channels. And during the process of carrying out DSM, substantial consumer interposing should be introduced in order to bring about a mutual consent and a successful implementation.

A fixed load control pattern is what has been in place for some time now. And it is proved to advantageous to control loads which do not require continuous supply of energy to operate normally. Real time control of loads would be a step further in DSM which is very well possible as a scheme under a larger distribution network automation programme.

Deferrable loads

"A deferrable load consumes a certain amount of energy to provide a service but is flexible in terms of exactly when that energy is supplied because it possesses either an internal storage capacity or a large thermal inertia or because the consumer is flexible about the time when he or she requires the energy service." [10]

DSM is used to regulate such deferrable loads remotely by the Distribution Network Operator (DNO). Smart meters could be employed to control such loads in real time at load centres. Such a set-up makes possible even real time measurements of load data for forecasting and further load control.

"Exploiting the deferability of loads is a useful tactic in any power system. It is especially valuable in systems relying on variable renewable energy sources, and can be far cheaper than employing energy storage." [10]

For example, in a typical household, the equipments' energy needs can be represented as shown below in Figure 2:

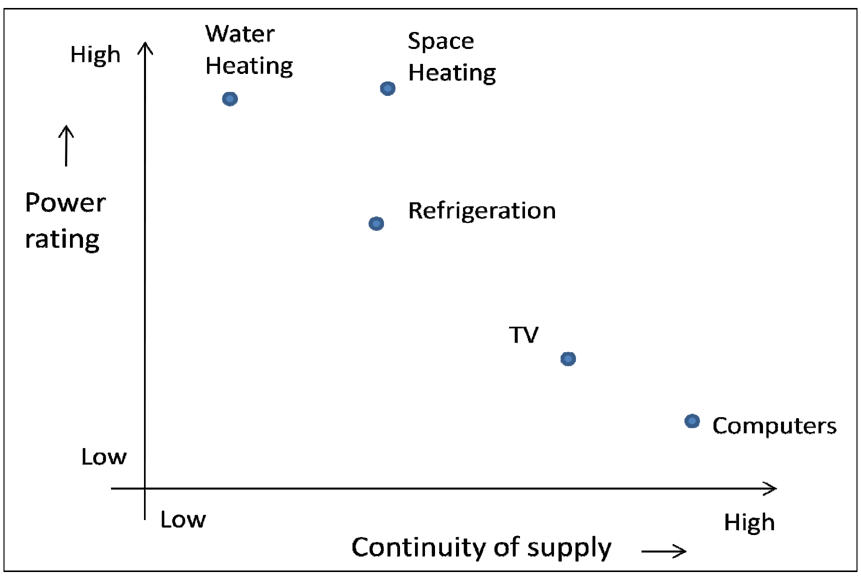


Figure 2: Power consumption versus supply continuity of residential loads [19]

We can observe that the higher power rated utilities are deferrable and a reasonable amount of energy savings could be achieved by doing the same. While sensitive equipment like computers require constant supply because even momentary interruptions can cause them to go out of service leading to data loss.

2.5 Distributed Generation (DG)

One of the definitions of DG is “An electric power source connected directly to the power network, preferably at the customer side of the meter, sufficiently smaller than the controlling generating plant.”[3]

Distributed Generation implies all generating sources on an electrical distribution network. The plant size could range from large co-generation plants to smaller capacity renewable energy sources like small wind energy conversion systems, solar photovoltaic, micro-hydro electric, biomass plants etc. Combine Heat and Power (CHP) installations are another major type of Distributed generation which has flourished in the past few years.

DG is classified based on the power generation capacity. A typical classification could be [3]:

- Micro – 1W to 5kW
- Small – 3kW to 5MW
- Medium– 5MW to 50MW
- Large – 50MW to 300MW

Climate change, energy cost and supply security are some of the major drivers behind the proliferation of distributed generation. In the UK, distributed generation connected to the network is growing considerably each year. Small scale wind turbines, biomass boilers and CHP units have been on a rise. All these do accelerate the move towards meeting the Government's targets for renewable and CHP generation by the year 2010 such as [1]:

- Produce 10% of the UK's energy needs from renewable sources
- Reach a total of 10GW of CHP generating capacity (approximately double the current capacity)

Introducing generation sources on distribution network poses problems for the normal operation of the network in terms of voltage and fault levels of the network. A power source within the network increases the network voltage at the node where it is connected. It is an advantage if the system voltage has reduced due to power losses in the lines and transformers. But the level to which the voltage rises makes a difference. Voltage levels higher than the nominal value affect the immediate customers by putting their equipment at risk. Renewable energy sources like wind, PV etc are intermittent in nature and thus have problems of discontinuous and irregular supply schedules. Wind systems have the constraint of variable power output depending on the wind speed in the region. Thus, problem of power quality exists. Also there is a possibility of such generation sources being operated when the rest of the network is dysfunctional or during a power outage. This leads to a situation called island operation. To prevent islanding, the energy source has to be isolated from the network when the utility supply is cut-off. It prevents maintenance people from accidents and also in the case of faults, sustained fault conditions. An automated performance monitoring scheme is needed to keep the network in nominal operating condition. By automating the distribution system different network management schemes like DSM and DG control can be implemented under the same framework and implemented efficiently. A step further would be to make the automation system compatible with real time monitoring and control to tackle the issues associated with the ever changing network configuration.

2.6 Distribution System Automation

The term Distribution Automation has a broad meaning and newer applications are added up frequently onto the list. Automation could be in the form of a communication system that controls the customer load and reduces peak load generation by automatic load management.

It may also be a more extensive system where an unattended distribution substation can be transformed to an attended one by installing an onsite microprocessor which monitors the substation continuously, make operating decisions, issue commands or reports changes in the system to the load dispatch centre, store data for future use depending on the requirements of the utility.

Distribution automation functions can be categorised into three main types:

a. Load management
b. Operational management
c. Remote meter reading

2.6.1 Level of penetration

The level of penetration of distribution automation refers to how deep into the distribution system the automation goes. The need for acquiring power system network performance data has increased in at present due to the following reasons:

a. Increased reporting requirements from regulatory authorities or government agencies.
b. Operating the electricity system close to the design limits.
c. Increased efficiency requirements due to increasing fuel prices.
d. Need to monitor lower voltages by the Distribution Network Operators. [7]

Studies suggest the following functional scope for the Distribution Automation Systems in the following years [7]:

a. Protection
    - Breaker failure protection
    - Synchronism check
b. Operational control and monitoring
    - Integrated voltage and VAR control
    - Feeder automation
    - Load shedding, data logging, transformer monitoring etc.
c. Data collection and system planning
    - Distribution SCADA
    - Automatic meter reading
d. Communications
    - Two way communication using one media

2.6.2 Load Management

Distribution automation provides for both load management scenarios:

- Direct control of customer loads and the monitoring necessary for ensuring that the programmed levels are achieved.
- Appropriate selection of metering registers to suit the tariff plan of the loads (for example where time of use rates are applicable).

Load management monitoring and control functions include:

- Monitoring substations and feeder loads
- Controlling individual customer loads

Customer - activated load management can be achieved by alerting the customer to change their usage pattern and by incentives like time of use rates. Distribution automation provides remote adjusting and monitoring (role of smart metering) of loads and hence aids the DSM program.

2.6.3 Impact of Load Management on Distribution System Planning

Load management's benefits are system wide. Alterations in the load patterns affect the demand on the generation facilities and also the loading on the distribution equipment. Load Management may be used to balance or reduce the loads on the substations and the lines, thus extending their life. Since there are both technological and economic benefits from load management, it becomes a definite part of the planning process of future networks or reconfiguration of the existing system. Distribution system planners have to equip themselves with tools to incorporate, monitor and control load management system into the existing network. Future system design must consider the evolving scenario of electrical power systems and as evident, it has a considerable level of uncertainty associated with it. "While it is impossible to foresee all the effects that technology will have on the way in which Distribution planning and engineering will be done, it is possible to identify the major forces which are beginning to institute a change in the methodology and extrapolate."[7]

2.8 Voltage Control

"Consumer loads comprise mainly heating and lighting elements, motors, electronic equipment providing audio video services, computers and controllers, battery charging facilities for portable equipment and finally electrochemical services mostly for industrial applications. All these loads are designed to provide their services from a nominally fixed voltage supply. Utilities are therefore obliged by law to provide electricity at consumer terminals at a voltage that does not deviate from the nominal value by more than a few percent with a maximum of ±10% not being uncommon. For this to be achieved at the extremities of the distribution network the voltage of all nodes moving up through the layers of increasing voltage in the distribution and transmission system should be kept close to their nominal value." [10]

The constraint to maintain the nominal voltage is the unavoidable voltage drop that occurs due to the impedance of the transmission lines, cables and transformers in the supply system. Various regulation techniques have been developed over the years to control system voltage. Some of the commonly used methods are [3]:

- Capacitor bank for voltage regulation and power factor correction
- Transformer tap changing (manual/automatic)
- Voltage – regulating transformers
- Phase shifter or regulating transformer

2.8.1 Transformer Tap Changers

Tap changers play an important role in voltage control. "Almost all transformers incorporate some means of adjusting their voltage by means of addition or removal of tapping turns. This adjustment may be made on-load, as is the case for many large transformers, by means of an off-circuit switch, or by the selection of bolted link positions with transformer totally isolated. The degree of sophistication of the system of tap selection depends on the frequency with which it is required to change taps and the size and importance of the transformer." [13]

Tap changers are installed in the power system for the following reasons:

a) To compensate for changes in the applied voltage on bulk supply and other system transformers.

b) To compensate for regulation within the transformer and maintain the output voltage constant on the above types.

c) On generator and inter-bus transformers to assist in the control of system VAR flows.

d) To allow for compensation for factors not accurately known at the time of planning an electrical system.

e) To allow for future changes in system conditions.

However, tap changers have some disadvantages:

a) Transformer impedance will vary with tap position and thus the system design must allow for this.

b) Losses will vary with tap position and hence the cooling arrangement must be capable of handling the maximum possible loss condition.

c) The increased number of leads in side the transformer increases complexity and possibility of internal faults.

d) On-load tap changers make the distribution transformer a significant source of unreliability. [13]

On-load tap changers are used in transformers except the secondary distribution transformers. The voltage range with the taps is usually ±10% the nominal value. The 11/0/415 KV transformers are supplied with off-load tap changers on the HV winding in order to suit the regional conditions of the distribution network.

Figure 3: On-load tap changer type UBBRN by ABB. [18]

The key control parameters available to network operators to manage the voltage on primary distribution networks are [12]:

- constraint of real power exported by generators,
- adjustment to the import (or export) of reactive power by generators and
- control of on-load tap-changers (OLTCs) at primary substations.

Automatic Voltage Controller (AVC) controls the tap changer in the transformer. The control algorithm allows for line drop compensation (LDC) in most cases. If min and max voltages on the distribution network are outside the limits of the feeder voltage levels then nothing is done (no voltage control). [9]

When tap change method of voltage control is used then the no. of tap changes may increase and thus the maintenance cost. But it is most likely to be less than network reinforcement costs and also postpones network reconfiguration plans for voltage reasons and allows connection of DG in the power system.

Abnormal distribution voltages can be introduced into the network due the following reasons [14]:

- *Mechanical problems*: Motor driven tap changing equipment is susceptible to repeated operation following a single control instruction. Under this situation the mechanism will drive the tap changer to the highest or lowest tap position, with the consequence of very high or low power system voltage. The only way in which the operation of the mechanism can be stopped is by disconnection of the motor power supply.

- *Electrical control problems*: Wiring, equipment faults or false voltages presented to the measuring relay will cause the tap change mechanism to be operated repeatedly and usually cause high voltages on the power system.

- *Abnormal feeding arrangements*: When LDC is used and distribution networks are operated abnormally under high load conditions, for instance to support a remote substation during fault repairs or maintenance, voltage levels can be driven above the normal high levels. While a wider tolerance of voltage deviation may be acceptable, a danger of high voltage exists if due attention is not given to the operational settings of the voltage control system under these conditions.

Implementation of a voltage control system with suitable settings on the fixed tap distribution transformers can give the following operational and business advantages for a DNO [14]:

- Flexible operation of distribution networks including parallel operation.

- Increased plant utilization

- Reduction in system losses

- Prevent or delay capital expenditure
- Optimise customer voltage levels for a given network
- Offer reliability under all network conditions
- Accommodate more generation within the distribution network

Chapter 3: Active Network Management

3.1 Active networks

Distribution systems were designed to receive power at high voltages from the transmission networks and distribute it to customers at lower and safe voltage levels. Behaviour of the distribution network is well understood and the procedures for both design and operation long established, even with interconnected networks. However, with significant penetration of embedded generation the distribution network is no longer a passive circuit supplying loads but an ‘active’ system with power flows and voltages determined by the generation as well as the loads.

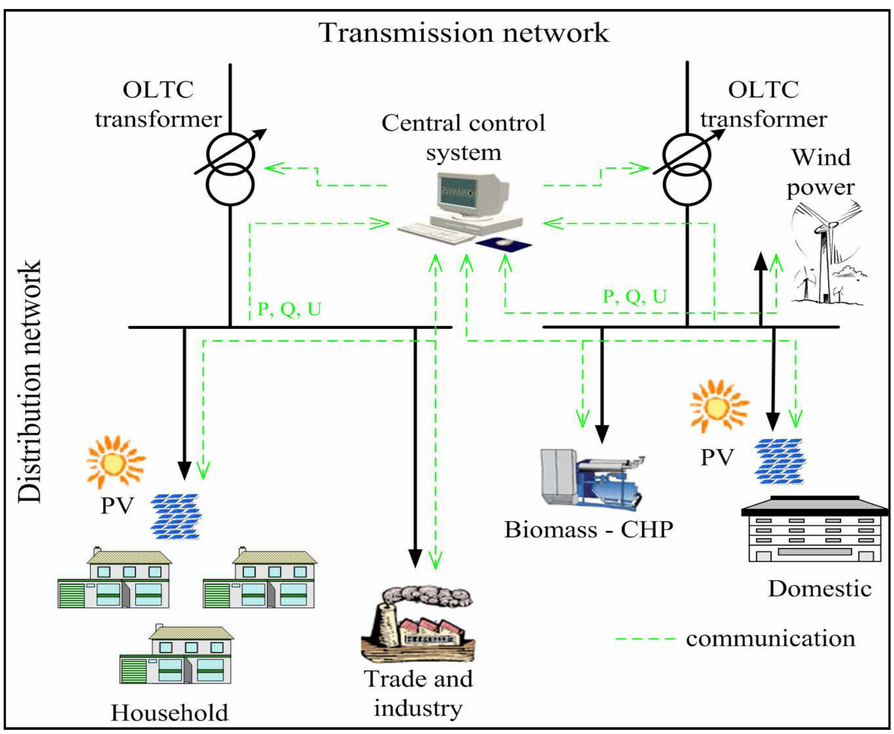


Figure 4: Active network example [21]

A cogeneration scheme with a synchronous generator will export real power when the electrical load of the installation falls below the output of the generator but may absorb or export reactive power depending on the setting of the excitation system of the generator. A wind turbine will export real power but is likely to absorb reactive power as its induction (asynchronous) generator requires a source of reactive power to operate. The voltage source converter of the photovoltaic (PV) system will allow export of real power at a set power factor but may introduce harmonic currents. Thus the power flows through the circuits may be in either direction depending on the relative magnitudes of the real and reactive network loads compared to the generator outputs and any losses in the network. The variations in power flows caused by embedded generation have vital technical and economic implications for the distribution system. Technical issues regarding connection and operation of embedded generation have been looked at in recent times. Solutions for most of the issues have also been found. But the effects of embedded generation on the overall network performance have to be studied further in order to bring optimal network performance and reliability. [16]

3.2 Control in Active Networks

Active control may involve the following tasks executed continuously:

- Measurement of system parameters, for example V, I, P, Q, f and network topology.
- Comparing these measurements with set values or with desirable values obtained from analytical computations of the network model, for example load flow analysis, contingency analysis, optimum economic dispatch etc.
- Activating a control element to implement the desirable changes, for example increasing the excitation of the steam input to a synchronous generator, opening or closing a transmission line etc.
- Checking the changes have been implemented and warning control engineers if the control actions fail. [10]

3.2.1 Active Network Voltage Control

Some DNOs use control of on-load tap changers of the HV/MV distribution transformers including the use of a current signal compounding the voltage measurement. One technique is that of line drop compensation and as this relies on an assumed power factor of the load, the introduction of embedded generation and the subsequent change in power factor may lead to greater uncertainty in operation if the embedded generator is large compared to the customer load.

Active voltage control may be implemented either using central Distribution Management System (DMS) controllers or by distributing the control functions among the various controllers associated with each item of plant (i.e. generators, tap-changers). However this choice is largely an issue of implementation only as the control philosophy proposed accepts the requirement for communication between the various items of plant. The control actions required are slow (e.g. change of tap-changer set-point or generator despatch) and so low cost, slow, communications systems will be appropriate. The overall control system will be arranged in a hierarchy with the controllers of the 33/11 kV substations communicating upwards to similar equipment in 132/33 kV substations etc. Particular attention must be paid to the consequences of failure of the communications systems and how the system then reverts to a safe state.

As indicated earlier, the degree of integration can vary from a simple local based control of generation to a coordinated control between distribution and generation facilities over interconnected distribution circuits. [16]

In this project, the control design ignores line drop compensation and is limited to a base case distribution network with embedded generation.

Chapter 4: Network Model

The Distribution Network considered for the study is of the ring type, which is quite commonly implemented in distribution systems globally. The network is assumed to have residential, office/commercial, small industries and a large process industry as loads. The kW values indicate the connected load on the network. Detailed load models are presented later in this section. The network model is as shown in Figure 5.

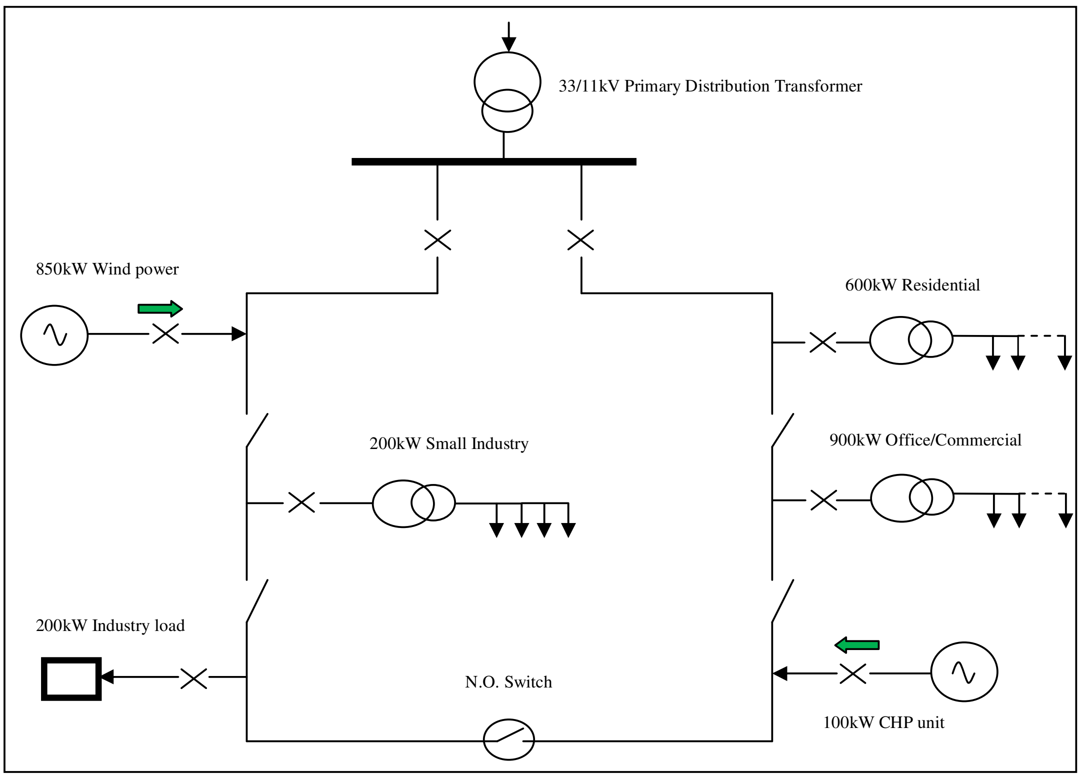


Figure 5: Example ring type distribution network

4.1 Load models and demand profiles

Load profiles are assumed for different times of the day keeping a maximum demand as reference and a percentage distribution of the end use of electricity within the considered loads (chosen from previous load forecast studies [18]).

Residential load:

A typical household with a connected load of 6kW is assumed for the study in this project. The ratings of the different loads in the household are assumed as given below. The assumptions are based on load profiles from previous load forecasting studies and are not physically measured.

End use	Weight
Hot water (boiler)	18%
Space heating and AC	20%
Lighting	10%
Refrigeration	15%
Cooking range	10%
Clothes washer	4%
Dish washer	3%
Other	20%

Table 1: Residential Load Distribution

On a typical day (winter), the demand profile appears as the chart shown in Figure 6.

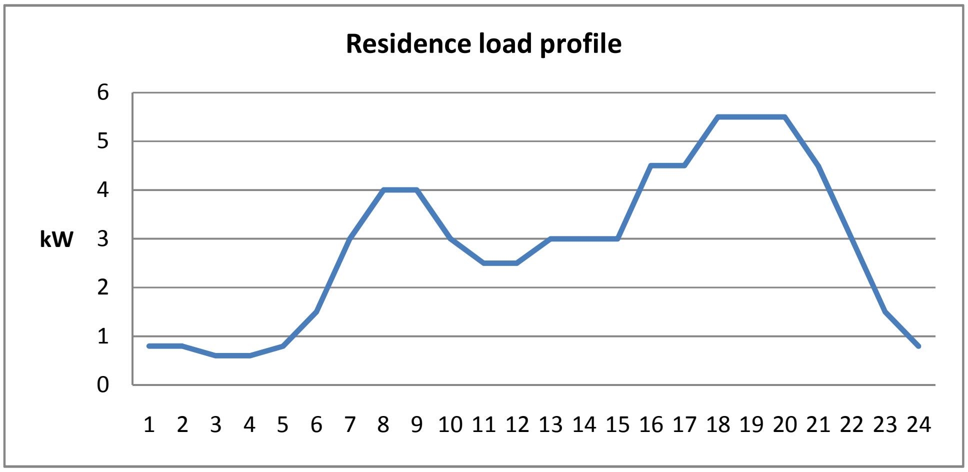


Figure 6: Residence load profile

Hundred such residential connections are assumed to be on the ring network totalling up to 600kW connected load.

Office/Commercial load:

Atypical office building with all the necessary amenities like lighting, space and water heating, office equipment etc is considered for the study. A connected load of 20kW is assumed. The capacity distribution is assumed to be as follows. (Representative figures referred from [11])

End use	Capacity
HVAC	45%
Lighting	20%
Equipment	20%
Lifts/escalators	10%
Miscellaneous	5%

Table 2: Office load distribution

The resulting profile on a typical day is as shown in Figure 7.

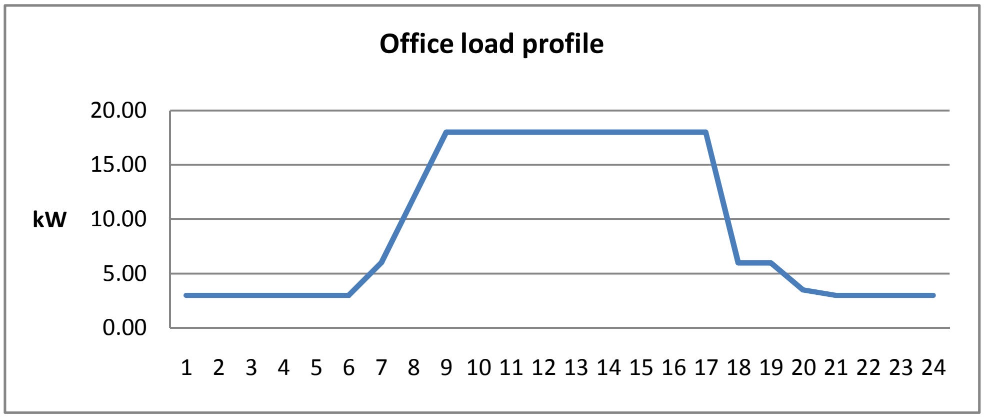


Figure 7: Office load profile

Fifty such office/commercial loads are considered to be supplied by the ring main.

Small Industry load:

A 50kW connected load, small industry/enterprise is considered for the study. The load distribution is assumed to be 60% Motor load and the rest being other loads.

Motors:

Qty	2 Nos.
Type	3 ph Induction motor
Rating	each 20hp = 14.92kW

Table 3: Motor load specifications

Other loads: *Lighting + HVAC + Miscellaneous = 20kW*

S	232.6 kVA
P	200 kW
Q	118.7 kVAR
P.F.	0.86 (overall)

Table 4: Small industry power flow

(S – Apparent power, P – Real power, Q – Reactive power)

The resulting profile is as shown in Figure 8.

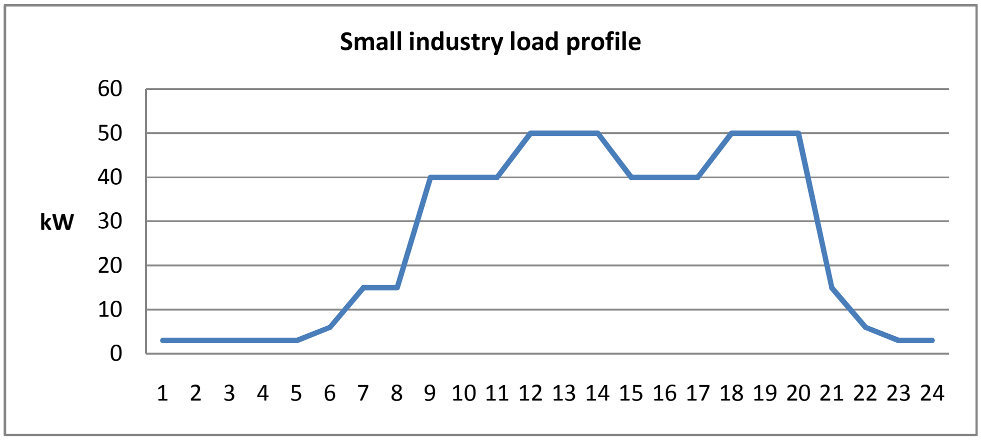


Figure 8: Small Industry load profile

Large Industry load:

A large load for example a process industry is considered with an installed capacity of 200kW. Motor load is assumed to be 60% of the total load.

Motors:

Qty	3 Nos.
Type	3 ph Induction motor
Rating	each 50hp = 37.3kW

Table 5: Industry motor load specifications

Other loads: *Lighting + HVAC + Others = 88kW*

Load flow:

S	250 kVA
P	200 kW
Q	150 kVAR
P.F.	0.8

Table 6: Industry power flow

The resulting profile is as shown in Figure 9.

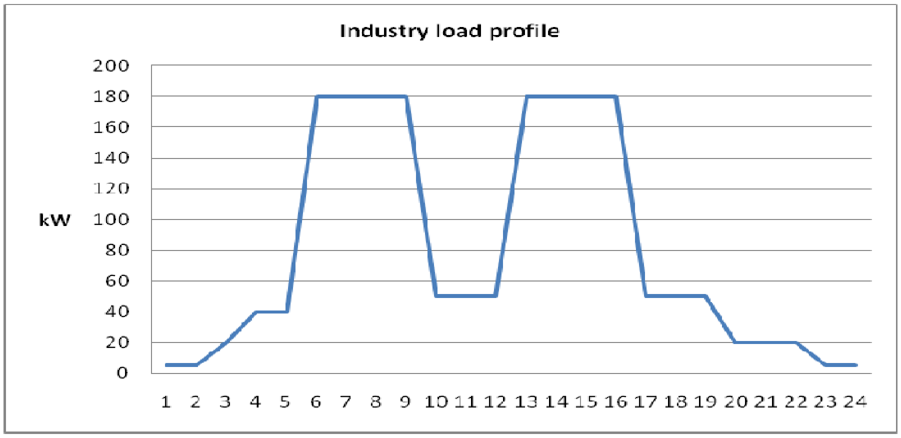


Figure 9: Large Industry load profile

4.2 Distributed Generation in the network

Wind Power:

A typical wind turbine of 850kW is considered for the study. Manufacturer specifications for the system are:

Description	Rating
Rotor diameter	52m
Rated speed	16m/s
Cut-in speed	4m/s
Cut-out speed	25m/s
Hub height	65m

Table 7: Wind turbine specifications

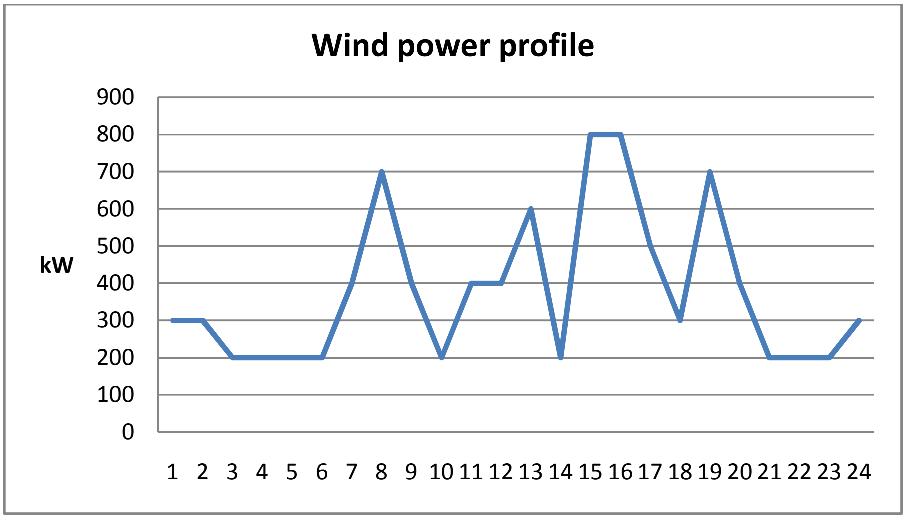


Figure 10: Wing energy profile

The wind turbine is never assumed to be in OFF state to suit the simulations. Since the wind energy conversion system model is being used in a real time simulation program, if the induction generator in the wind energy system is swithced off suddenly, then the network enters a state of instability and the simulation is brought to a halt. In order to avoid this, a minimum power output is maintained from the turbine at all times.

Combined Heat and Power (CHP) unit:

A total 100kW electrical power output from 20 CHP units of 5kW each is assumed for the study. The generation profile is assumed in line with normal activities in a day and times when space and water heating is required. The CHP unit generates power at the corresponding time intervals. It is assumed that the unit generates 80kW maximum at normal operating conditions.

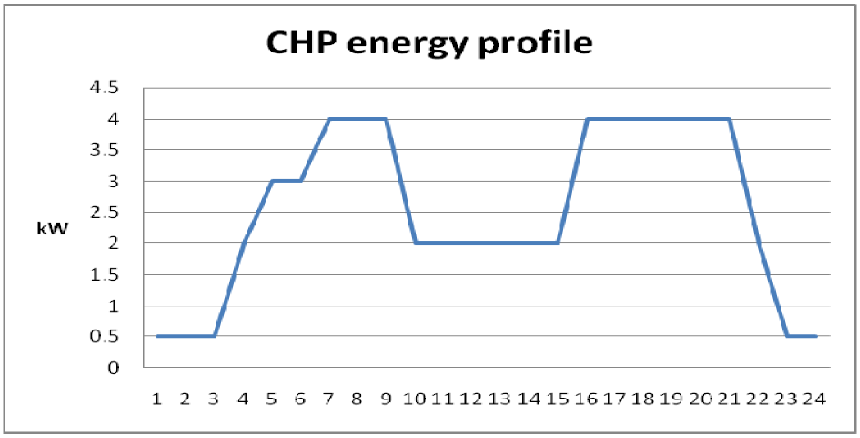


Figure 11: CHP Energy profile

Overall load curve and DG profile are obtained as shown in Figure 12.

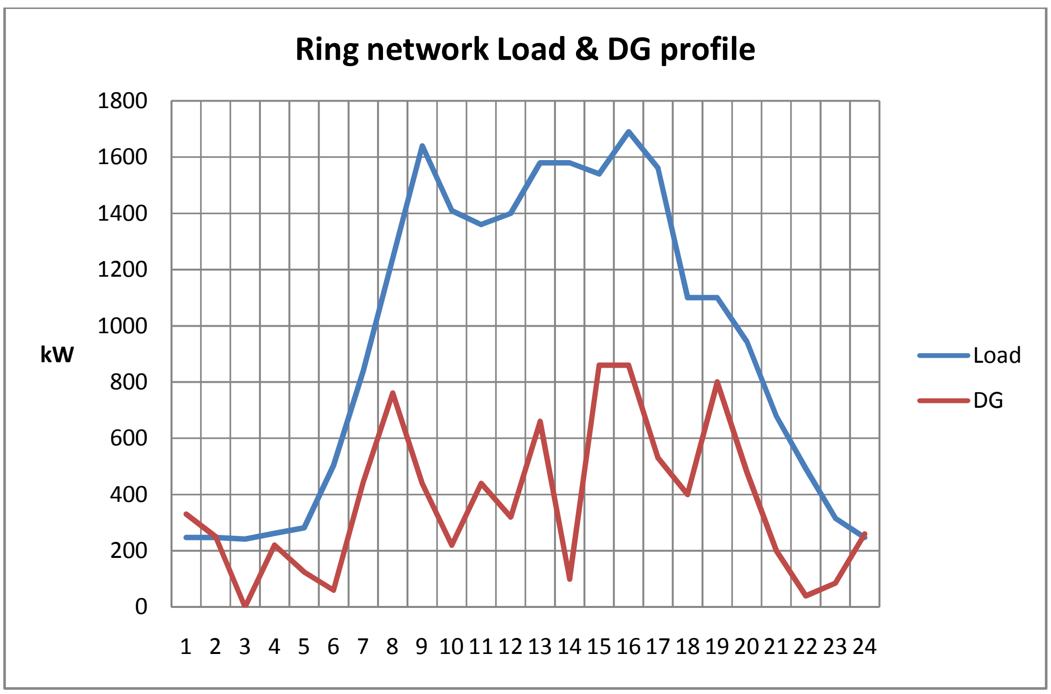


Figure 12: Total Load and DG profile for a typical day

Load type considered for simulations:

For implementation in the simulations, all the loads on the ring main are modelled as constant impedance loads and thus they do not operate at constant power at all times. The power consumption varies corresponding to the current flow and voltage applied to the loads. However, most loads in reality are constant power type and thus require varying current supply (constant voltage preferred) to maintain the constant power output. A mathematical representation of constant impedance loads can be given as below [3]:

If S = Apparent power (kVA)
V = Voltage (volts)
I = Current (amps)
And Z = Impedance (Ω)

$$S = VI^*$$

$$S = V\left(\frac{V}{Z}\right)^* = \frac{V^2}{R - jX_L} = \frac{V^2}{R^2 + X_L^2}\left(R + j\,X_L\right)$$

Where, R and XL are constant values of active and reactive load impedance respectively.

Chapter 5: Active Network Control System Development

The control system is designed and implemented in two stages in this project. The first stage being the load control stage. Individual loads are switched ON/OFF using the controller. It is assumed that a switching pattern is decided in advance and the same is loaded onto the controller for the next interval. Load forecasting is assumed to be done based on previous load data and also availability of DG and the number of controllable loads on the network.

The controller is intended to be installed on the feeder at the primary substation and send control signals to local switching devices (passive breakers/ intelligent devices like smart meters).

The second stage of the control system is the voltage control system, in which the voltage and power at the feeder is measured and the distribution transformer tap position is controlled correspondingly. Tap-up and tap-down signals are sent from the controller to the tap changer to maintain the system voltage at a nominal value and also control voltage rise due to connection of distributed generation on the network. The controller displays the tap position at all times, intimating the operator of the occurrence of tap change. Voltage control becomes one of the important aspects of active network management and thus an attempt to design a simple real time control is made in this project. Various assumptions are made and the very basic network conditions are considered for the study at this stage.

5.1 Controller selection

A multifunctional, robust and simple programming run control system had to be chosen for the application. Programmable logic controllers have been a tried and tested option in the manufacturing, power and control systems. And PLC's have evolved into better control units ever since their inception. Ladder logic is used to program the controller. Since ladder logic is a graphical programming technique using simple relay contacts, timer, counters and other functional blocks, it is not a tedious task to program the PLC.

Also software packages are available which make the programming much easier by giving an option of verifying the ladder logic, online editing with PLC and also support data logging functions in some models of controllers.

5.2 Programmable Logic Controller (PLC)

Early control systems were based on relays which allow power to be switched on and off without a mechanical switch. It is common to use relays to make simple logical control decisions. The development of low cost computer has brought a revolution, the Programmable Logic Controller (PLC). The advent of the PLC began in the 1970s, and has become the most common choice for manufacturing controls. PLCs have been gaining popularity on the factory floor and will probably remain predominant for some time to come. Most of this is because of the advantages they offer.

- Cost effective for controlling complex systems.
- Flexible and can be reapplied to control other systems quickly and easily.
- Computational abilities allow more sophisticated control.
- Trouble shooting aids make programming easier and reduce downtime.
- Reliable components make these likely to operate for years before failure. [15]

Programmable Logic Controllers were initially developed for discrete control applications in machine and materials handling production engineering environments. The ongoing development of PLC's for the control and monitoring of industrial systems has increased their capabilities from simple hard wired logic elements advanced functions using software-controlled microprocessors for piping and instrumentation diagram algorithms, floating point arithmetic, network communication and multiple processor configurations for parallel processing. Modern PLC's are capable of handling power system local control automation requirements. [8]

They have some useful features like inbuilt Ethernet cards for network communication, RS-232 ports for hardwire links and also better memory and I/O (analogue, digital, relay contacts, high speed outputs etc.) for complex programming. One of the major advantages of PLC's is that, they are modular in nature and can easily be expanded according to the application requirements. The basic unit can control additional I/O modules and also can communicate with intelligent I/O which have control functions embedded within them for onsite functions and send the required data to the main control unit using the communication links.

The specific model used in the project is the Allen Bradley Micrologix 1100. This model consists of 10 digital inputs (0 – 24Vdc), 6 relay outputs, 2 Analogue inputs (0-10V), enough memory to hold the logic and data logging. It has a LCD screen to display status of I/O, operation mode or customised display from the application. The LCD function also allows the operator to enter values using the key pad without having to reprogram or connect to a programming device. The main unit is used for the project, but the controller supports additional I/O and thus the system can be easily expanded based on the application.

Figure 13: Allen Bradley Micrologix 1100

Ladder logic is used to program the controller. A software package called RSLogix 500® is used to compile the program and load it onto the controller. An interfacing program called RSLinx Lite® is used to interface the PLC with the PC on which the programming is carried out. These software packages are available from Rockwell Software and are readily available.

Appendix of this report gives the product specifications.

5.3 Ladder logic programming

Ladder logic is the main programming method used for PLCs. It has been developed to mimic relay logic. This method has evolved due to the past existence of relay logic circuits in industrial and power control systems. These relay contacts are used as switches to create logic functions.

A relay is a simple device that uses a magnetic field to control a switch, as pictured in Figure 14, when a voltage is applied to the input coil, the resulting current creates a magnetic field. The magnetic field pulls a metal switch (or reed) towards it and the contacts touch, closing the switch. The contact that closes when the coil is energized is called normally open. The normally closed contacts touch when the input coil is not energized. Relays are normally drawn in schematic form using a circle to represent the coil. The contacts are shown with two parallel lines. Normally open contacts are shown as two lines, and will be open (non-conducting) when the input is not energized. Normally closed contacts are shown with two lines with a diagonal line through them. When the input coil is not energized the normally closed contacts will be closed (conducting). [15]

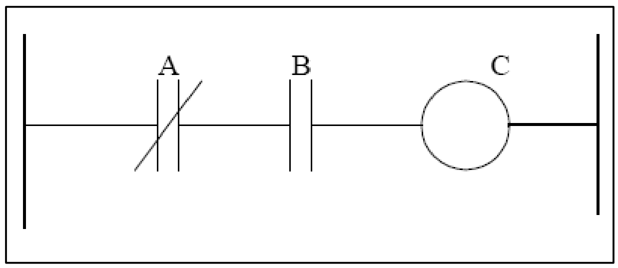


Figure 14: Simple relay controller

Relay logic is expressed graphically in rungs one over the other, with the left pole representing the line (positive) and the right pole being the common (negative). When the logic is laid out in such rungs and viewed together, it appears to be in a ladder form and thus the name ladder programming.

An example of ladder logic can be seen in Figure 15. To interpret this diagram, imagine that the power is on the vertical line on the left hand side, we call this the hot rail. On the right hand side is the neutral rail. In the figure there are two rungs, and on each rung there are combinations of inputs (two vertical lines) and outputs (circles). If the inputs are opened or closed in the right combination the power can flow from the hot rail, through the inputs, to power the outputs, and finally to the neutral rail. An input can come from a sensor, switch, or any other type of sensor. An output will be some device outside the PLC that is switched on or off, such as lights or motors. In the top rung the contacts are normally open and normally closed. Which means that if input *A* is on and input *B* is off, then power will flow through the output and activate it. Any other combination of input values will result in the output *X* being off.

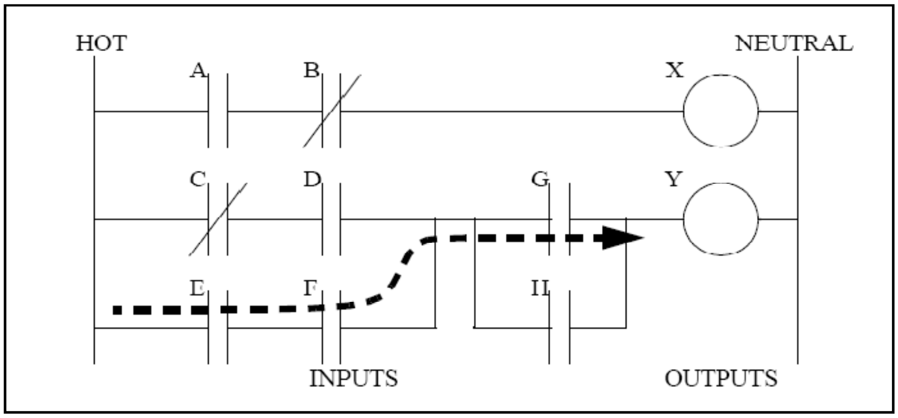


Figure 15: Simple ladder logic diagram

The second rung of Figure 15 is more complex, there are actually multiple combinations of inputs that will result in the output *Y* turning on. On the left most part of the rung, power could flow through the top if *C* is off and *D* is on. Power could also (and simultaneously) flow through the bottom if both *E* and *F* are true. This would get power half way across the rung, and then if *G* or *H* is true the power will be delivered to outputs *Y*. [15]

5.3.1 RSLogix 500

RSLogix 500 software is a 32 bit Windows ladder logic programming package for the SLC 500 and Micrologix® processors. RSLogix 500 includes:

- A free form ladder editor hat lets you concentrate on the application logic instead of syntax as you write your program.
- A powerful project verifier that you use to build a list of errors you can navigate to make corrections at your convenience.
- Drag and drop editing to quickly move data table elements from one data file to another, rungs from one subroutine or project to another, or instructions from rung to rung within a project.

- An address wizard that makes entering addresses easier and reduces keying errors.
- Search and replace to quickly change occurrences of a particular address or symbol.
- A point and click interface called a project tree that lets you access all the folders and files contained in your project.
- A custom data monitor to view separate data elements together and observe interactions.
- Trending and histogram functionality for monitoring and displaying process data.
- SLC libraries for storing and retrieving portions of ladder logic for use across any of Rockwell Software's SLC programming software products.
- A compare utility that lets you graphically view project differences.

The control algorithm has to be loaded onto the PLC (Micrologix 1100) using a computer. A communication link has to exist between the programming device and the controller to achieve this. Communications from RSLogix 500 take place through another software package, called RSLinx Classic Lite. RSLogix 500 talks to RSLinx, which in turn talks to your communications devices.

A *driver* is a small piece of software that allows a computer to talk to other systems. In this case, RSLinx Classic uses drivers to connect the computer to the processor (Micrologix 1100). The user has to tell RSLinx Classic what driver is needed to use to make that connection. The driver used depends on the way the processor is physically connected to your computer. There is a wide variety of possible physical connections; it is important to know which type of connection the system is using and how that physical connection is configured. [17]

The main project window in RSLogix appears as shown in Figure 16.

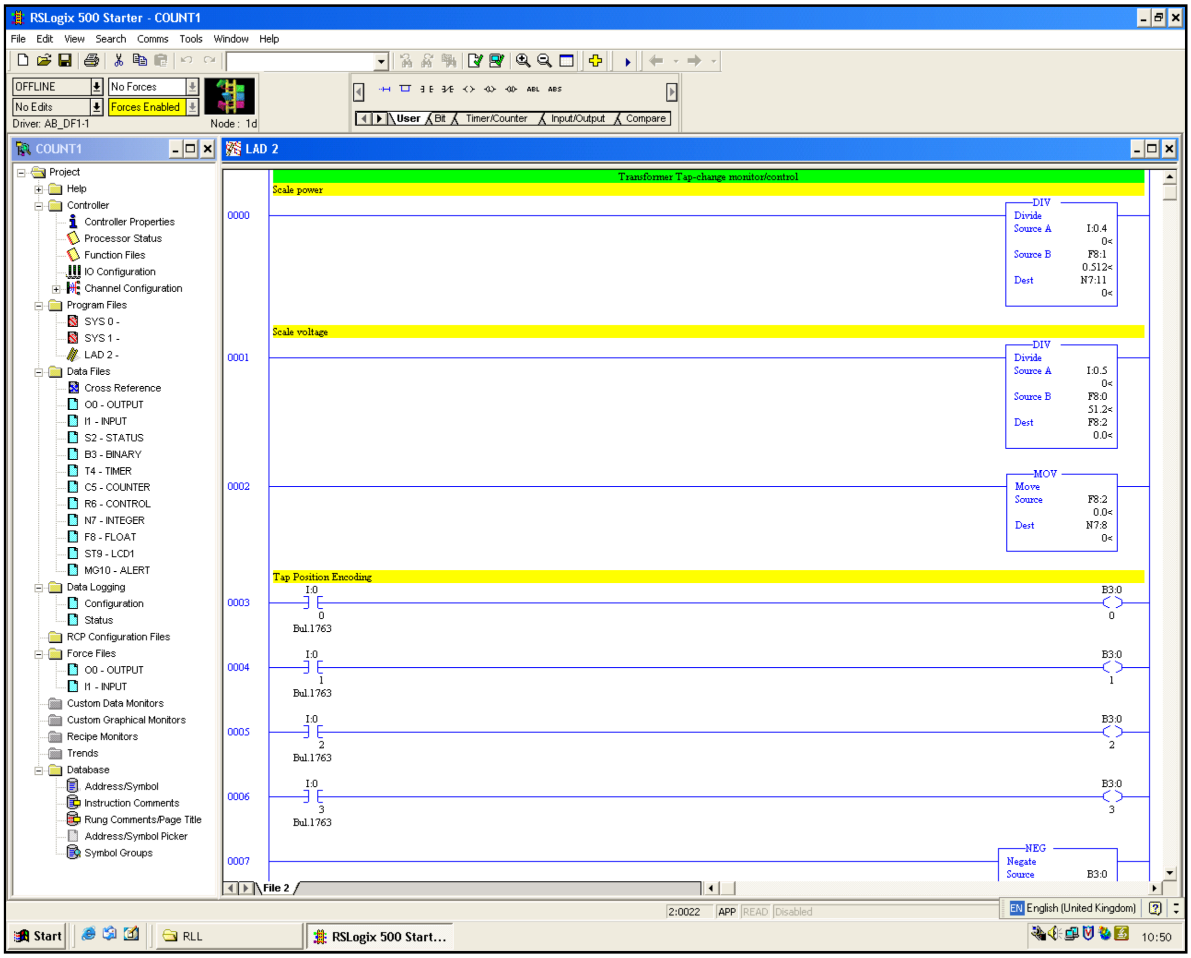


Figure 16: RSLogix project window

5.4 Control Design

5.4.1 Load switching

Application Requirements:

1. The PLC has to switch 4 individual loads connected to its relay output terminals. A 24 hour period is considered for the study. For the simulation, each hour in real time is made equivalent to 1 min and thus a 24 min real time simulation is run. At each minute, the switching pattern has to be read from a data table and the same moved onto the output channels in sequence.
2. Read voltage and power measurements at the feeder bus and input to the PLC through the two analogue inputs. Display the readings onto the controller's LCD screen.

Switching pattern:

Here, it is assumed that the operators are aware of regular load behaviour and are provided the DG supply profiles well in advance to make their switching decisions.

Demand profiles of all the loads are combined to form a load curve for the ring main. The overall availability profile of the DG is also prepared and the possible intervals for shifting the loads to reduce peak power, higher load factor and maximum utilization of DG are identified. Then which of the loads are to be ON/OFF at what interval of the day is decided.

For example if the large industry load in the network model is switched OFF during the day time and switched ON during the night and early morning hours (off peak), then the following pattern is obtained as in Figure 17.

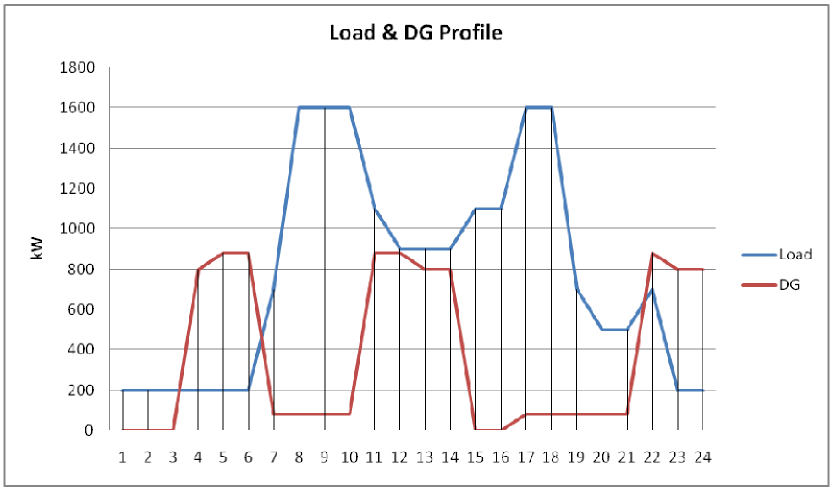


Figure 17: Load & DG profile after implementing load switching

If we compare this plot with the original profiles, then we can observe that considerable peak load reduction and valley filling is obtained. Also the energy supplied by the DG is utilized in better percentage in this form. However the switching decisions depend on deferability of loads and availability of DG.

A binary state table is prepared based on the forecast for the load switching. In this case, to suit the requirements of the I/O of the real time simulator, an active low logic is used. i.e. a bit high (1) represents OFF condition (breaker) and bit low (0) represents ON condition. The following is a state table (Table 8) which represents one of the switching patterns. Such patterns are loaded onto the data tables of the PLC from where the program reads the data and energizes corresponding outputs.

Hour	Res	Office	Small-Ind	Ind
1	1	1	1	0
2	1	1	1	0
3	1	1	1	0
4	1	1	1	0
5	1	1	1	0
6	1	1	1	0

Hour	Res	Office	Small-Ind	Ind
7	0	1	0	1
8	0	0	0	1
9	0	0	0	1
10	0	0	0	1
11	1	0	0	1
12	1	0	1	1
13	1	0	1	1
14	1	0	1	1
15	1	0	0	1
16	1	0	0	1
17	0	0	0	1
18	0	0	0	1
19	0	1	0	1
20	0	1	1	1
21	0	1	1	1
22	0	1	1	0
23	1	1	1	0
24	1	1	1	0

Table 8: State table for load switching

Two such switch patterns have been prepared and implemented for the study during the project.

Flow chart:

The flow chart below represents the logic used in programming the PLC for the load switching task. A sequencer function is used in the ladder logic programming to move the switch pattern from the data tables onto the output channels. The change takes place every minute as per the design requirement. A simple on delay timer is used to realize this function.

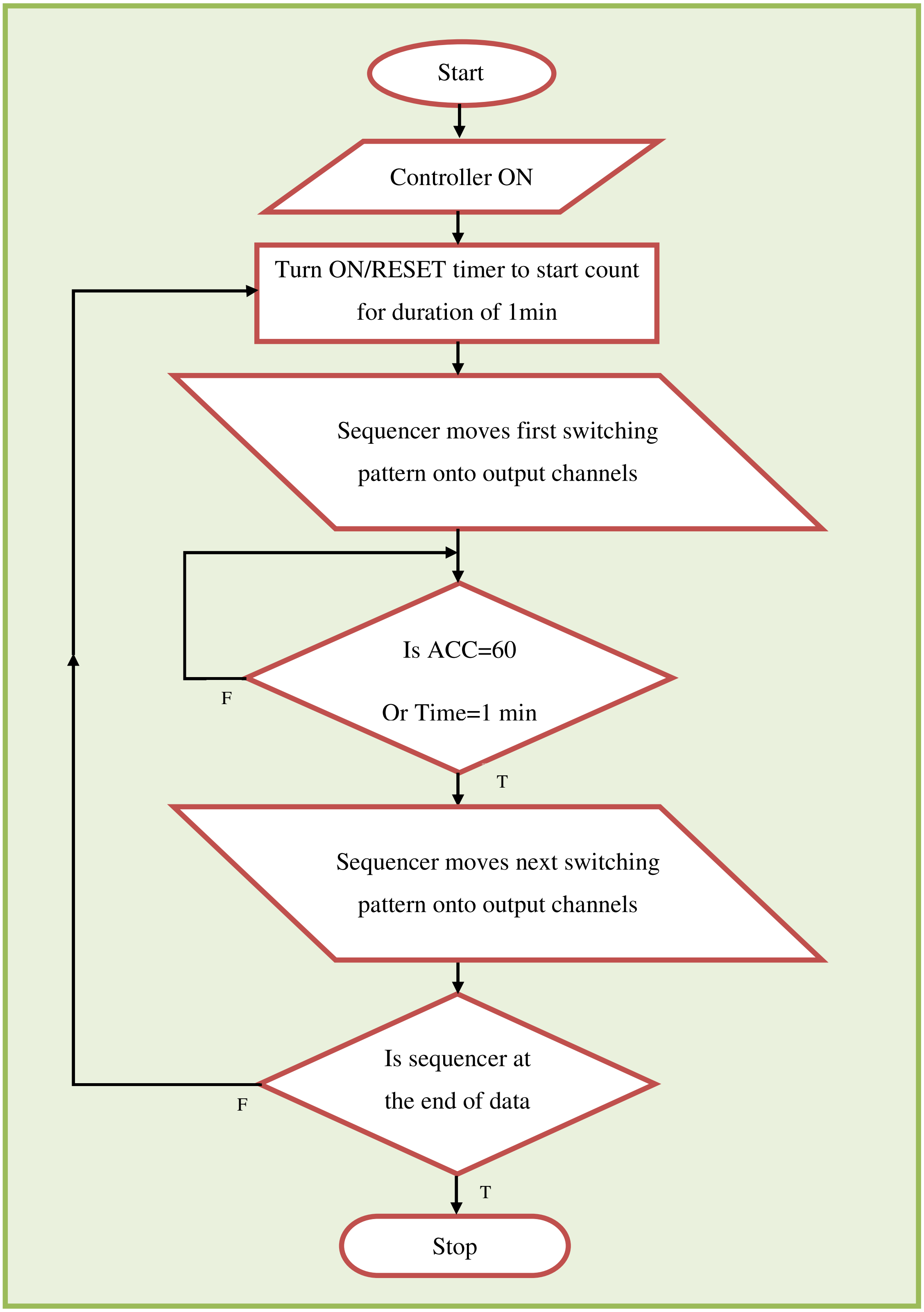


Figure 18: Load switching algorithm

5.1.2 Voltage control

Application requirements:

1. Read the position of the tap changer of the primary distribution transformer and display the same on the controller's LCD screen. Position is encoded onto digital channels in decimal format and fed to digital inputs of the PLC.
2. If position of the tap is beyond safe limits then a system alert is displayed.
3. Voltage and power at the feeder is measured and fed to the PLC through the analogue channels and displayed on the controller screen.
4. Tap-up and tap-down of the on load tap changer is controlled corresponding to the power fed to the ring network at a given time instant and voltage levels.
5. If the power flow in the feeder bus exceeds a certain limit compared to the preceding value, then the tap-up signal is initiated. If the power measured at real time is less than the specified limit from the preceding value, the tap-down signal is initiated. However, the network voltage is checked before the actual tap change signal is initiated. The voltage measured will be real time value.
6. A 30 sec (equivalent to 30min in real time) time period is specified for updating the preceding power value with which the real time power value is compared with.
7. The total number of tap changes in a given period of time is counted and can be accessed by the operator by going online with the PLC at any time and check the count register.

Since the tap change control is implemented individually, the load curves are preloaded into the simulation program (RSCAD). With time, the simulation tracks the load curves and corresponding power is fed to the network. Changes in power flows are detected and also voltage levels are measured to initiate tap change operation.

Flow chart:

A combination of timers, counters, relay contacts etc is used to realize the logic for the voltage control system. Allowance for Line Drop Compensation (LDC) in tap change control and the delays in mechanical switching are ignores while setting trigger pulses and an arbitrary value is chosen. The traditional method of voltage control is done by sensing system voltage at the feeder and at the far end of the network and to maintain nominal values by controlling the tap position. But here, the real power flow to the network is also considered as a parameter to decide the tap change operation. This is in order to accommodate for the connection of DG when they come ON/OFF the ring main. So a sudden increase or decrease in power flow is considered for changing tap position also checking for the system voltage. This is done as an alternate method of voltage control and in view of the ever changing network configuration due to distributed generation and DSM being introduced into the existing distribution networks.

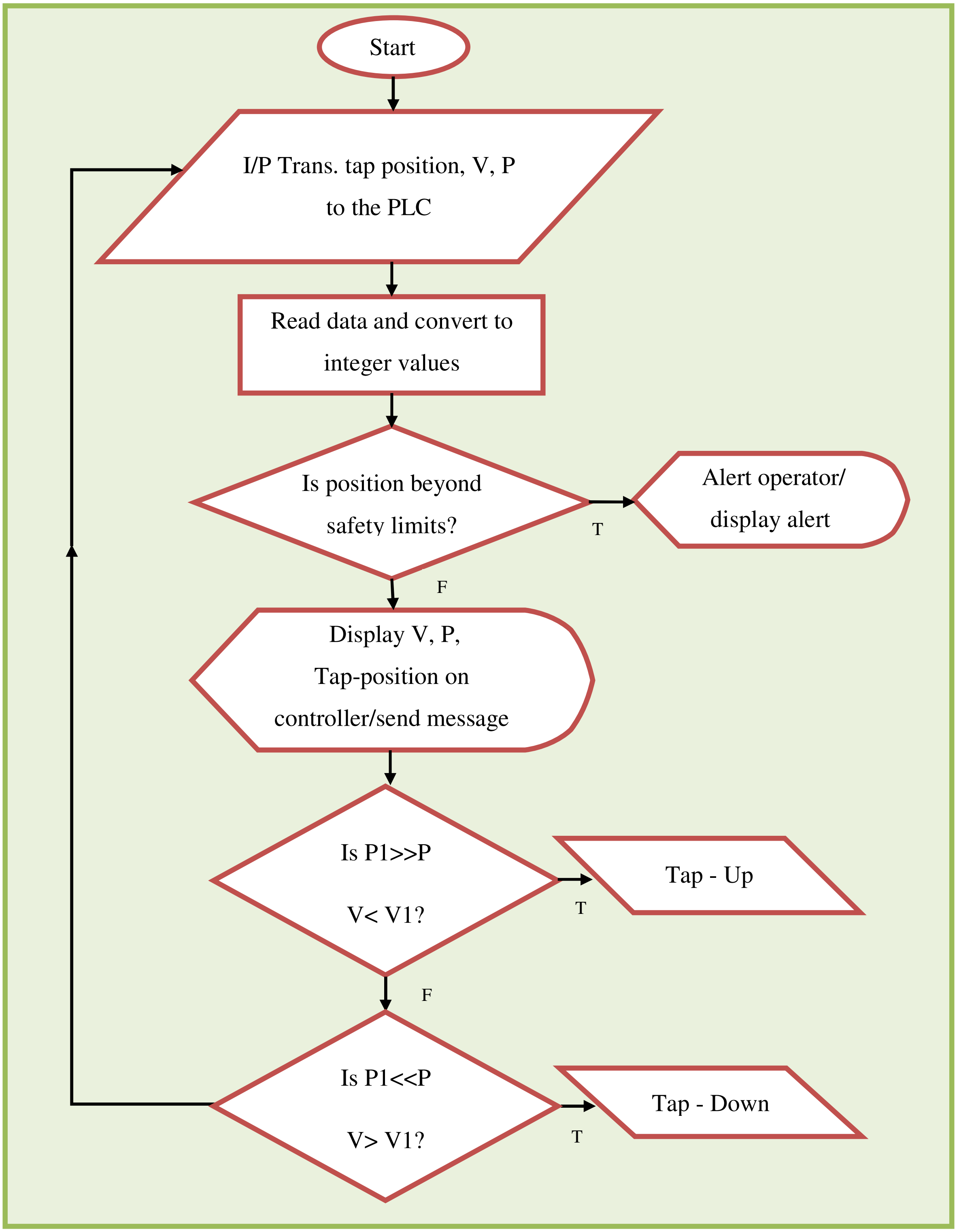
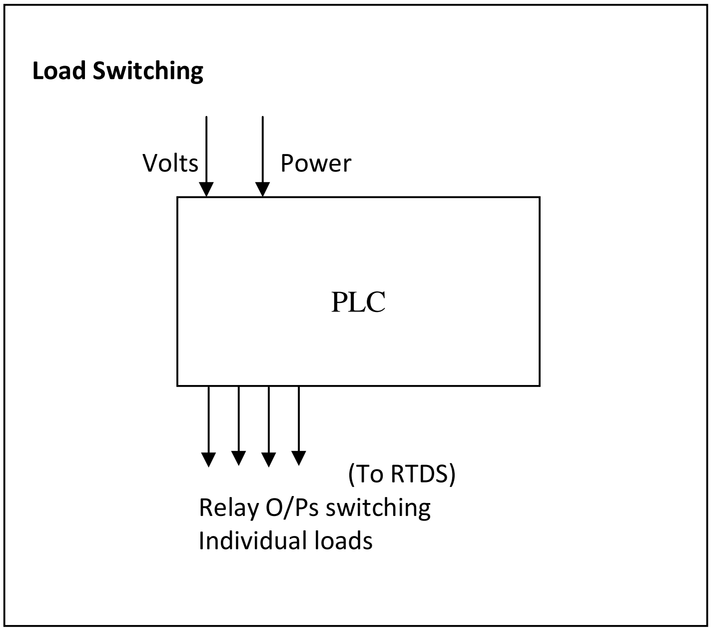


Figure 19: Voltage control algorithm

Schematics:

The following schematics in Figure 20 represent the PLC hardwire connections.



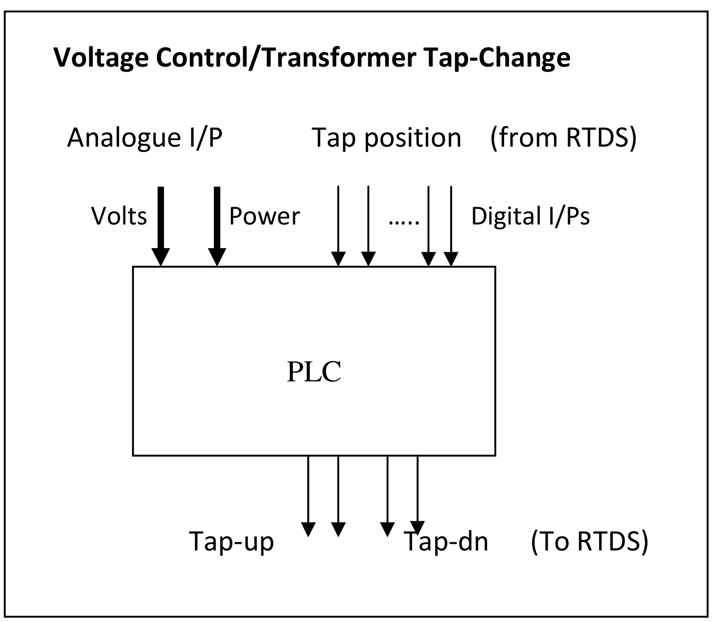


Figure 20: Schematics for controller wiring

Chapter 5: Simulation of Active Network Control

The simulations are carried out the real time digital simulator (RTDS). For the study, a network model as shown in the previous chapter was chosen. The model was prepared as part of another project in the department and was implemented here with some modifications to suit this particular project. A software program called RSCAD is used to draft the model and RSCAD also provides the graphical user interface for monitoring the simulations and to extract results.

The real time simulator is manufactured by RTDS Technologies Inc., Canada. The following section gives an overview of the simulator and the RSCAD program.

5.1 Real Time Digital Simulator (RTDS)

The RTDS simulator performs fully digital electromagnetic transient power system simulation in real time utilizing the Dommel Algorithm similar non-real time emtp programs.

The RTDS simulator is a modular, fully digital power system simulator that can be used for a wide range of studies, including:

- Performing analytical power system simulation
- Testing protective relay systems
- Testing control systems
- Education and training

The simulator takes advantage of a custom parallel processing hardware architecture assembled in modular units called racks. Each rack contains slot (max. 20) and rail-mounted cards. The racks are installed in one of four sizes of cubicles. The specific composition of an RTDS Simulator depends on the processing and I/O requirements of the intended application. A common communications backplane links all rack mounted cards facilitating information exchange. Each rack's backplane functions independently so that communication of data can be done in parallel thereby reducing communication bottlenecks.

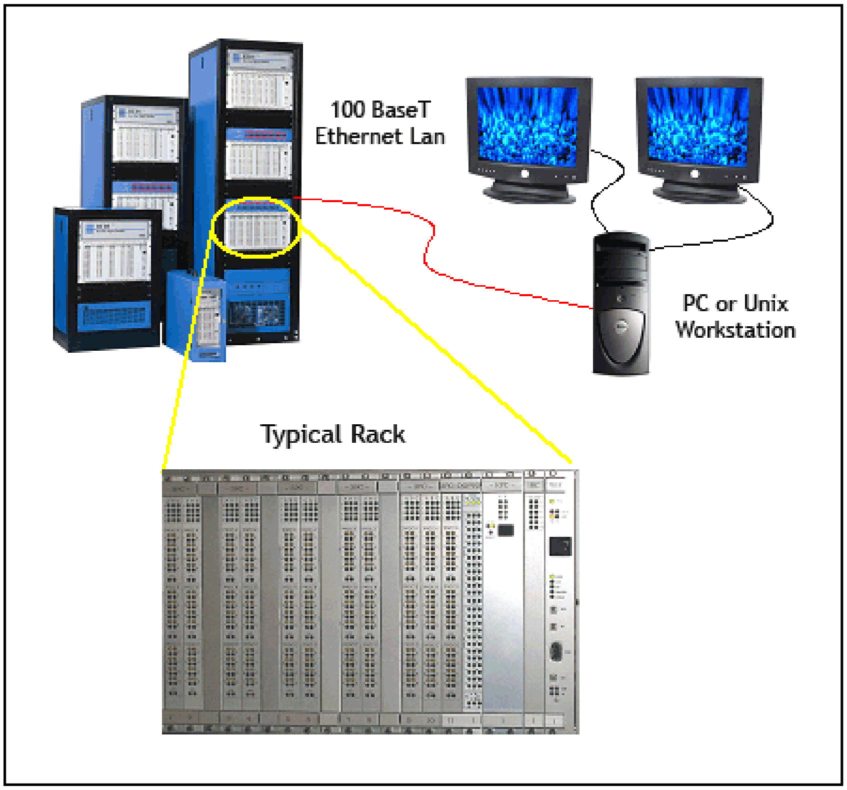


Figure 21: Real Time Digital Simulator (RTDS)

Apart from the digital I/O cards and analogue channels, the High voltage digital interface panel was used in the project. The programmable logic controller (PLC) requires a min of 14Vdc input signal. Since the regular I/O channels have a limit of 0 to 5Vdc, the HV digital interface panel was used for the purpose, supplied by an external DC source.

High voltage panel specifications:

The High Voltage Panel provides 16 solid-state contacts rated for up to 250Vdc which can be controlled directly from the Simulator's digital output ports.

The interface panel is used either to bring high voltage digital inputs into the RTDS Simulator or to send digital outputs from the RTDS Simulator to dry contacts.

Digital Input Modules - the digital input modules are used to input up to 280 Vdc into the RTDS Simulator. Different modules must be used for different input voltages. The input range can be 180-280Vdc. The voltage level must be decided before manufacturing the panel. The typical time delay of the input module is approximately 20msec.

Digital Output Modules - the digital output modules are used to control solid-state contacts using the RTDS Simulator's digital output ports. The output module solid-state contacts are rated for a maximum of 250Vdc. A diode connection is also provided with the panel for the case where inductive loads are applied. The typical time delay of the output module is approximately 0.5msec.

The RTDS® Simulator employs an advanced and easy to use graphical user interface - the RSCAD Software Suite. This software is the user's main interface with the RTDS hardware. The software is comprised of several modules designed to allow the user to perform all of the necessary steps to prepare and run a simulation and to analyze simulation output. All modules provide graphical representation and mouse driven operation by click, drag, pull down menus, or push button action creating a working environment familiar to the power system engineer.

RTDS Simulation has two main software elements:

Graphical User Interface

RSCAD provides the ability to set up simulations, control, and modify system parameters during a simulation, data acquisition, and result analysis. The modules of RSCAD Software Suite include: FileManager, Draft, Tline, Cable, RunTime and MultiPlot.

Library of Power and Control System Component Models and Compilers
The RTDS software also includes a multitude of power and control system component models, which can be used to create simulation cases. These models have been designed and tested by our research team at RTDS Technologies and have been validated and refined by our clients during their daily work with the Simulator.

The Power and Control System Software is an integral part of RSCAD for RTDS®. RSCAD allows the user to select a pictorial representation of the power system or control system components from the library in order to build the desired circuit. Once the system has been drawn and the parameters entered, the appropriate compiler automatically generates the low-level code necessary to perform the simulation using the RTDS Simulator. Therefore, this software determines the function of each processor card for each simulation. [20]

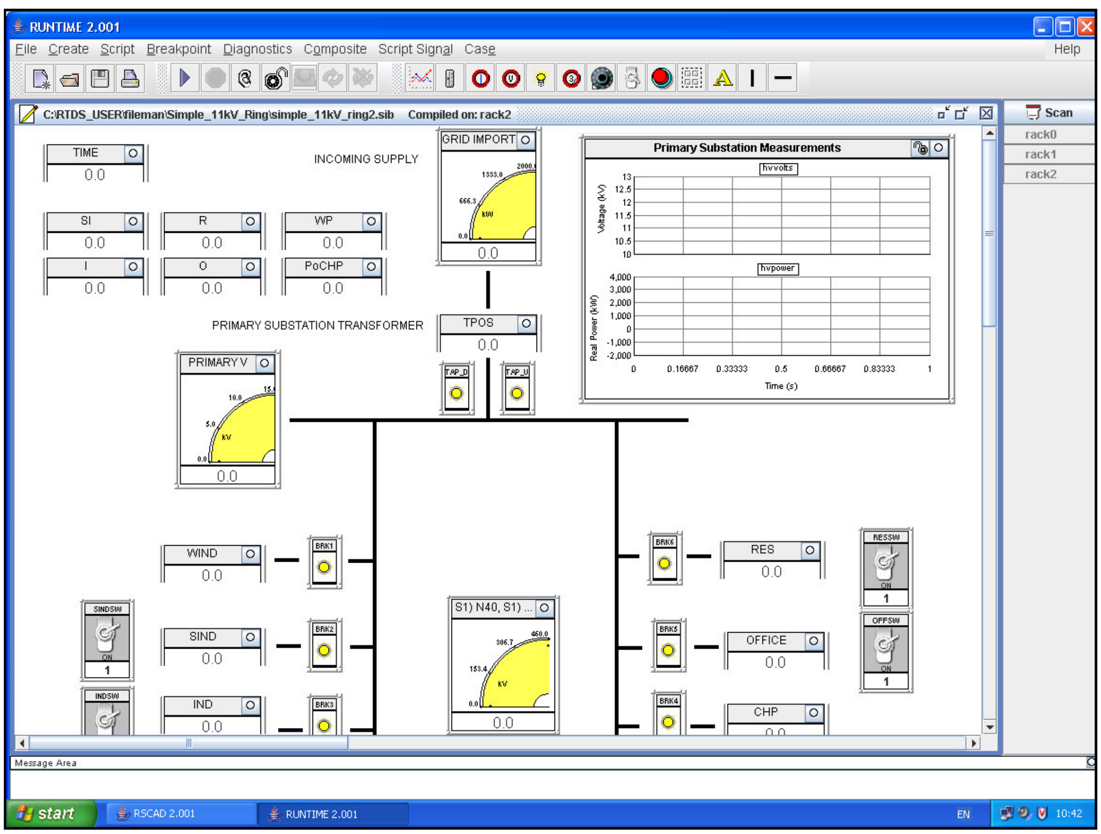


Figure 22: RSCAD Runtime window

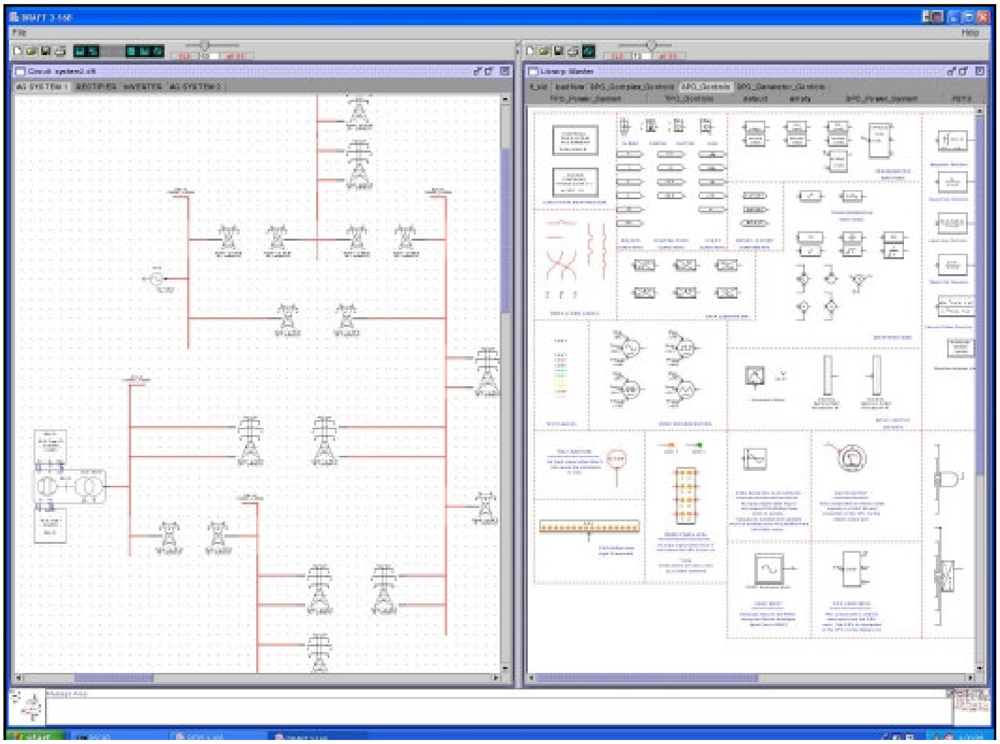


Figure 23: RSCAD Draft window

- For the project, hardwire contacts were run between the simulator and the PLC. Each of the loads to be switched on the network model was controlled by circuit breakers which operate on receiving commands from the controller.
- Analogue channels were connected to the PLC inputs to provide the voltage and power measurements from the RTDS to the controller.
- The voltage control mechanism was implemented separately by connecting digital inputs of the simulator to PLC outputs to initiate tap change signals.
- The simulation program RSCAD is run on the local area network enabling any PC on the network can function as a host.

Chapter 6: Simulation Results Analysis

Load Switching:

One of the switching patterns is loaded onto the PLC data tables and the program is run with the real time simulator running the network model. The sequencer in the PLC program puts the pattern of loads (ON/OFF) onto the output channels which are connected to the simulator racks which in turn switch the load models on the network. Since the outputs from the PLC are relay outputs, each breaker associated with the four individual loads are wired with the digital input rack on the simulator.

When one of the loads is switched on by the controller, there is voltage transient on the feeder bus which can be visualised on the voltage plot. With corresponding power flow increase there is a momentary dip in voltage and it settles down after a short range of oscillations as shown in Figure 24.

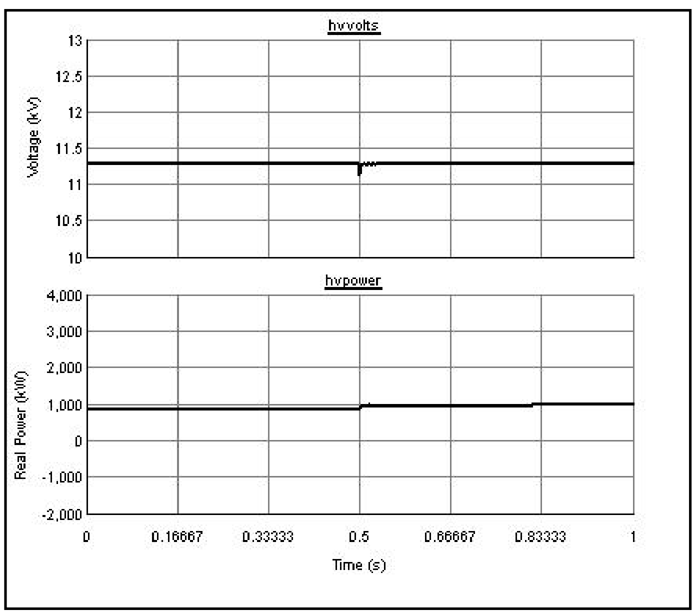


Figure 24:   Voltage variations due to varying loads

Such observations can only be made in transient level simulators like RTDS and are vital for power system protection studies.

In the network model considered for the study, when the small industry load is switched off, the following variations shown in Figure 25 were observed in the simulations. The first of the two graphs represents the feeder bus voltage in kV and the second, real power supplied by the feeder in kW.

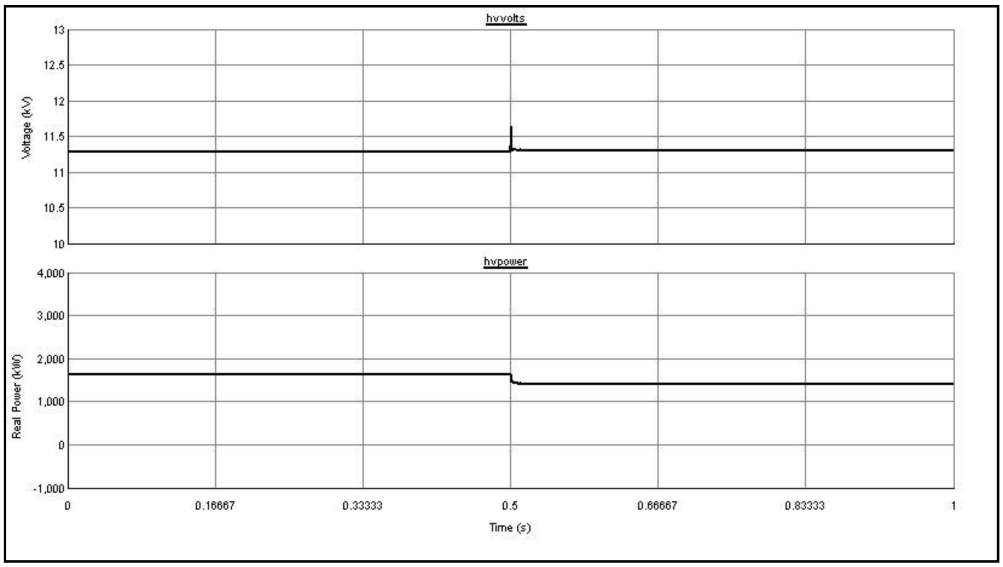


Figure 25: Small industry load switched off

The plots represent a small interval of the real time simulation. The changes are captured at the instant and plotted as shown above. This is one of the advantages of using the real time digital simulator (RTDS), that when a simulation is running continuously, changes in performance of the network can be visualised at a short interval from their occurrence with corresponding time interval also provided. Also the plots can be adjusted for user requirements in terms of scale the time period for which the data is reloaded, max and min values etc as in any graphical user interface enabled simulation program.

When the controller is running the switching pattern, the loads are switched ON/OFF corresponding to the pattern specified. Some of the load switching instants during the simulation are captures and presented here.

Small Industry (SIND) and residential (RES) loads are ON. The illuminated blocks (circuit breaker) represents the ON state in the screen as shown in Figure 26.

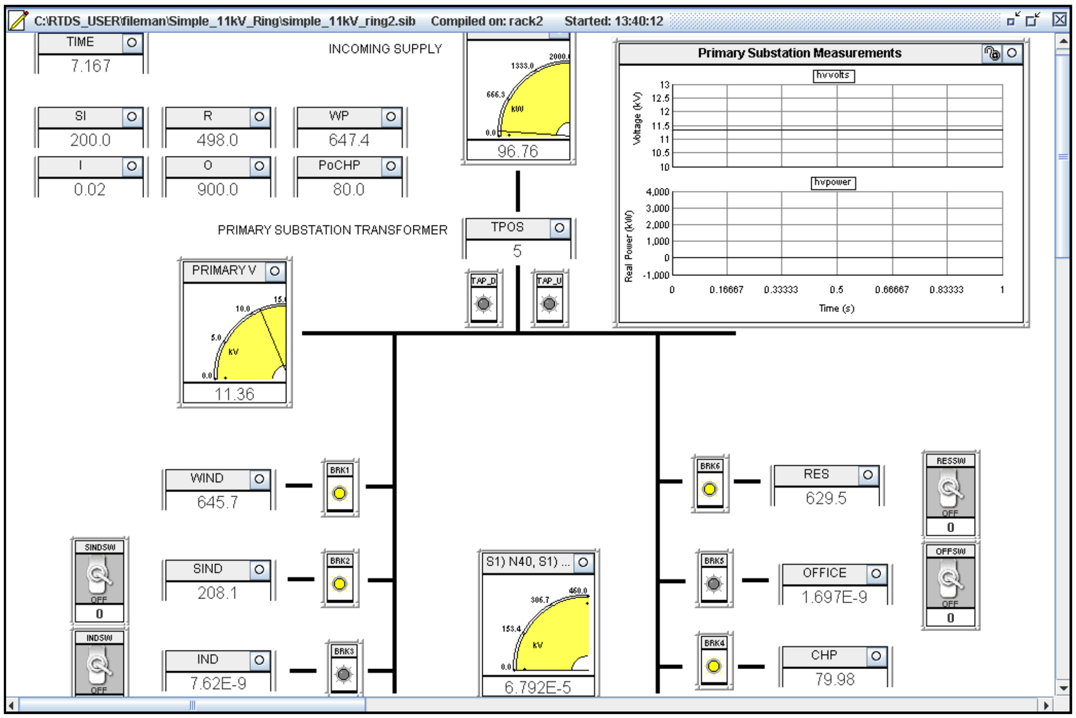


Figure 26: Small industry and residential load ON state

In the above snapshot, we can also observe that only 96kW out of the total load requirement of about 830kW is supplied by the primary distribution substation. All the remaining power is supplied by the DG connected to the network. The wind energy system is supplying about 645kW and the CHP units about 80kW of power. Therefore, DG is being utilised to its maximum at this hour in the day. The switching pattern is designed to achieve such a supply mix, since the availability of DG is predicted and the load curves are modified to make maximum use of the DG.

This situation occurs at approximately the 7th minute during the simulation. If we go to the switching pattern decided for the day and check the 7th min as highlighted in Table 9, we can observe that the small industry and the residential loads are supposed to be ON at this time period. (Since they are active low inputs, '0' represents ON and '1' represents OFF state).

Hour	Res	Office	Small-Ind	Ind
1	1	1	1	0
2	1	1	1	0
3	1	1	1	0
4	1	1	1	0
5	1	1	1	0
6	1	1	1	0
7	0	1	0	1
8	0	0	0	1
9	0	0	0	1

Table 9: Load switching pattern highlighted

Voltage control

Tap changing of the On-load tap changing transformer is the method used for voltage control. When the PLC switches the tap position up/down during the simulation based on the power flows and the voltage levels on the system, the resulting performance changes are recognised and plotted by RSCAD program. Some of the observations are presented here along with the snapshots of the RSCAD runtime screen at the instant of tap change.

When a tap-up operation is executed, there is a voltage rise in the system and the same is recorded as shown below in Figure 27.

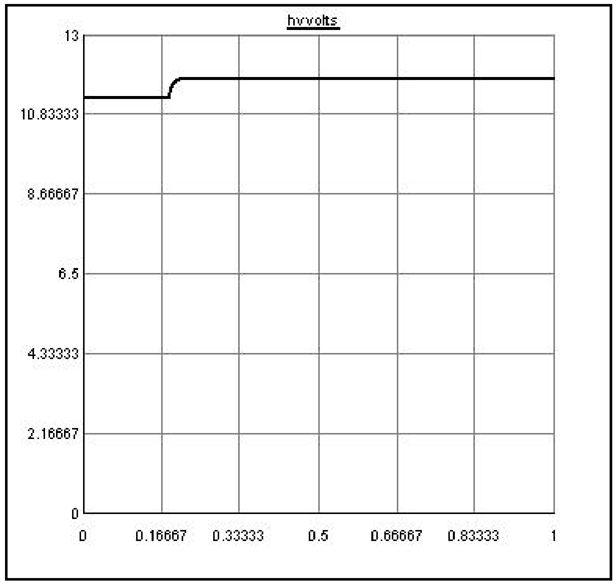


Figure 27: Tap - up operation resulting in voltage rise

It can be observed from the above graph that voltage level has risen from 11.3kV to 11.8kV at the feeder bus.

The following tap change was triggered due to a large load (Office) being added to the network during the simulation. The controller sensed the rise in power flows compared to the preceding value and the dip in system voltage level and triggered the tap – up signal. In the snapshot below, the illuminated contact named [TAP_U] just below the tap position indicates that the controller has passed a tap – up signal to the simulator. And the tap position which was 5 has changed to 6 after this initiation. We can also observe the switching transients in the graph of voltage and power within the snapshot in Figure 28.

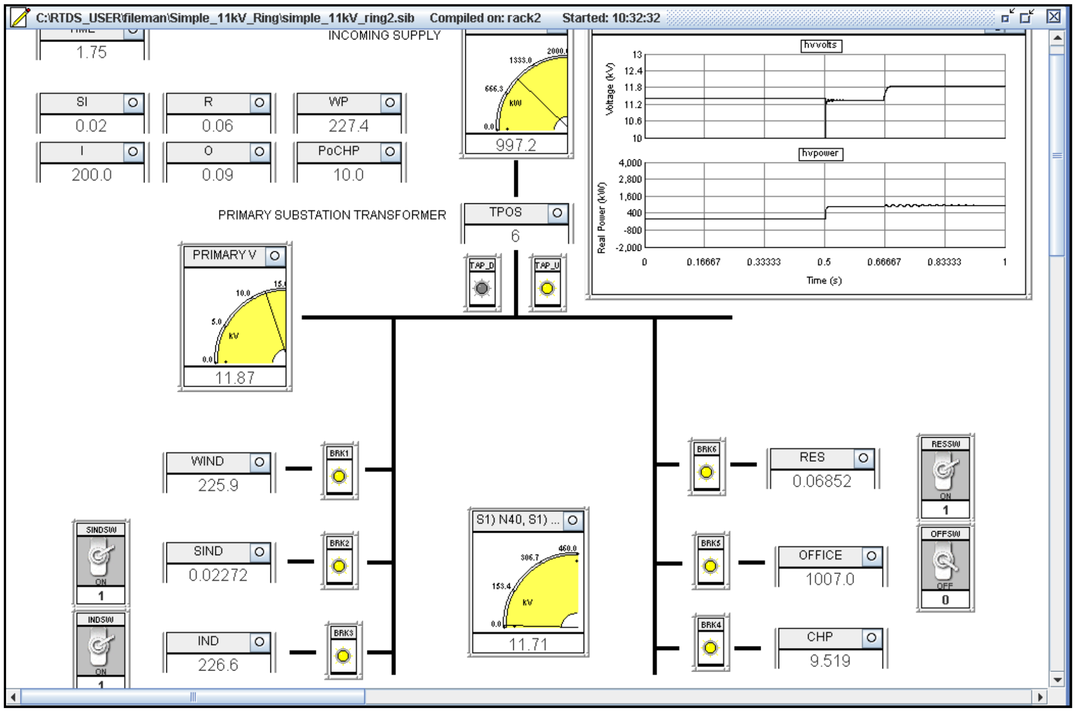


Figure 28: Tap - up operation snapshot

Similarly, when a voltage rise occurs or a large load is taken off the network suddenly or DG is connected to the ring main, then a tap down operation is executed. The snapshot below represents the tap down operation. The illuminated contact named [TAP_D] shows that the PLC has just initiated a tap down signal to the simulator owing to the load reduction/ voltage level rise.

In this particular case, the far end voltage on the ring main is 11.26kV which is beyond the set limit (11.1kV) and the feeder voltage is above 11.4kV and thus the tap change occurs. If the voltage levels are within the safe limits, then the controller does not change the tap position of the OLTC transformer.

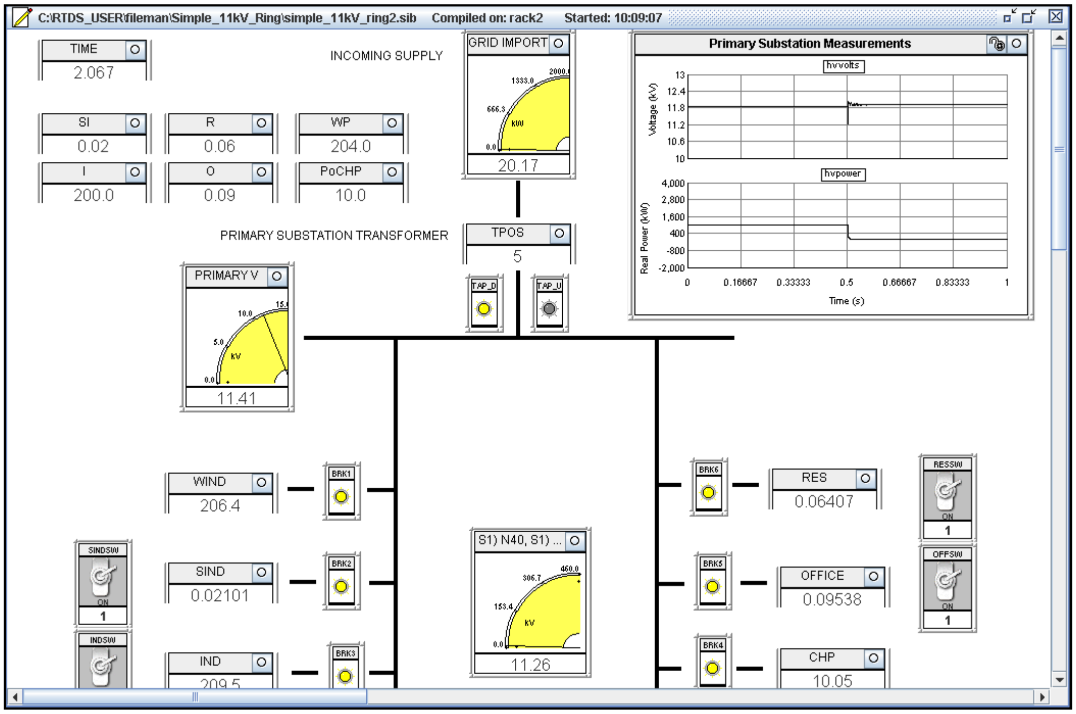


Figure 29: Tap - down operation snapshot

The system voltage and real power supplied from the feeder and tap position on the OLTC transformer is displayed on the LCD screen of the PLC. Figure 30 shows the display where the PLC is in 'RUN' mode and network voltage is 11kV, power supplied by the feeder is 1355kW and the position of the on-load tap changer is '6'.

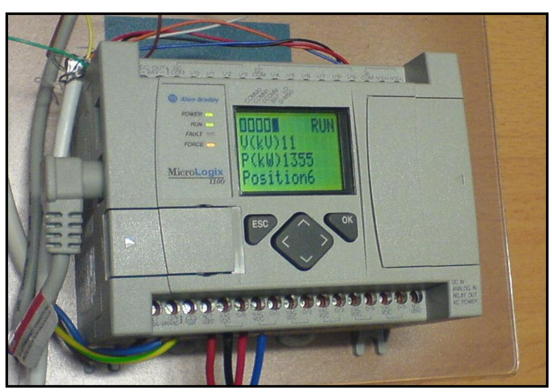


Figure 30: LCD Display on the PLC

Tap position is an important parameter to be put on display or sent to the operator as a message, as it ensures the tap change operation has occurred and also if there is hunting or multiple tap change operation, then the operator can take action accordingly. Since the controller can be communicated during operation, real time changes can also be made by the operator like switching the tap position manually.

Energy consumption:

It is assumed that the total energy consumed by the loads in day is the same during both the switching patterns and normal operation. As a result of load switching, it was observed that the energy supplied by DG with load shifting has increased in the two cases compared to normal operation. This means less power generated from the central power generators where mostly carbon intensive fuels are used, thus reducing green house gas emissions to the atmosphere.

	Case	Total Energy consumption (kWh/day)	Energy supplied by central generation (kWh/day)	Energy supplied by DG (kWh/day)
1	Normal operation	18700	14120	4580
2	Switching pattern 1: Industry load is shifted to off peak intervals	18700	12740	5960
3	Switching pattern 2: Large and small scale industry loads, short interval of office and residential loads (heating) shifted to off peak intervals.	18700	11260	7440

Table 10: Energy Consumption in the ring main

In the above Table 10, the energy consumption over a typical day is listed. Carbon dioxide (CO_2) emissions in each case can be calculated. The Department of Environment Food and Rural Affairs (DEFRA) guidelines [22] specify that CO_2 emissions of 0.43kg/kWh (long term marginal factor) are to be considered for studies like energy saving calculations. By using this rate of emissions, the following Table 11 is prepared.

Energy supplied by central generation (kWh/day)	kg CO_2/kWh	Total emissions (kg/day)
14120	0.43	6071.6
12740	0.43	5478.2
11260	0.43	4841.8

Table 11: Associated CO_2 emissions

The energy generated only by the central generation units is considered here since the DG includes a wind energy system and CHP units. It is assumed that the CHP units run on clean fuels.

From the above table we can observe that CO_2 emissions can be reduced corresponding to better utilization of renewable generation on distribution networks.

Total energy consumption can be reduced by operating the network at the right voltage levels. In case of constant impedance loads (as modelled for the network under study), the power consumption varies with network voltage levels. For example, consider a network with voltage variations between 10.6 to 11.6kV where 11kV is the nominal voltage.

Voltage (kV)	Real power (kW)	kWh/day
10.6	898.88	21573.12
10.9	950.48	22811.52
11	968	23232
11.3	1021.52	24516.48
11.6	1076.48	25835.52

Table 12: Power consumption in constant impedance loads at different operating voltages

Assuming a load of constant impedance equal to 100Ω operating at a power factor 0.8, the power drawn at different voltages is calculated and listed in Table 12. It can be observed that voltage reduction can actually reduce the power and corresponding energy consumption in case of constant impedance loads.

But in reality there are constant power loads on the distribution network which vary current intake to maintain constant power consumption. For such loads the behaviour with voltage variation is different. With higher operating voltages, the power losses can be reduced in case of constant power loads which leads to a reasonable amount of energy savings over the distribution network.

Therefore depending on the type of loads on the distribution network and the voltage range at which these loads can operate normally, voltage control can be planned on the distribution network resulting in energy savings.

Chapter 7: Discussion and Conclusions

In this project a simple control system was designed and implemented for operation with a real time simulator. The specific objectives of the project were to develop a control system using a programmable logic controller to implement load switching and network voltage control schemes and test the same on a sample network through simulations. The challenges faced to realize the project objectives were to program the PLC, interface it with the Real Time Digital Simulator (RTDS) and setting the signal compatibility so that the control loop works without any problems. Both the controller and the simulator have their own graphic user interface programs through which operations can be monitored. Real time operations are also possible through these user interfaces and thus enable the operator to have access to system behaviour at present state and also the future operations.

It is experienced that designing and implementing control systems for power systems is a complex task. The fact that there are multiple control environments and each with different configurations in terms of physical quantities measured, equipments controlled and control algorithms used, integrating all of them is a challenge. Protocols of communication, I/O ratings, level of modulation of signal transmission, noise and other such issues are important during control design in the power system environment.

The controller thus developed is able to actively control network voltage levels by transformer tap change operation and load control by load switching. A set of results has been analysed in this thesis. The project has opened up avenues for more complex and sophisticated control schemes to be implemented in the simulation environment. Since real time performance monitoring is possible with such a setup leading to better control and automation schemes with respect to Active Network Management being implemented and tested. The results have been helpful in understanding some of the following issues.

7.1 Energy consumption:

Voltage control and demand side management results in the overall reduction of energy consumption on the distribution network. Firstly, due to load factor improvement leading to better load curves with peak power reduction. Individual loads are switched such that they operate at good voltage levels and power loss reduced by avoiding high current feed. Operating at required power rating means better efficiency of equipment and thus leads to savings on energy cost for the consumer.

By preparing load switching schedules based on load forecast and matching them with DG profiles can result in maximum utilization of renewable energy sources and other cogeneration and reduce GHG emissions as well. The charts in Figure 31 and 32 show the increase in energy supplied by DG and corresponding decrease in CO_2 emissions for the distribution network under study.

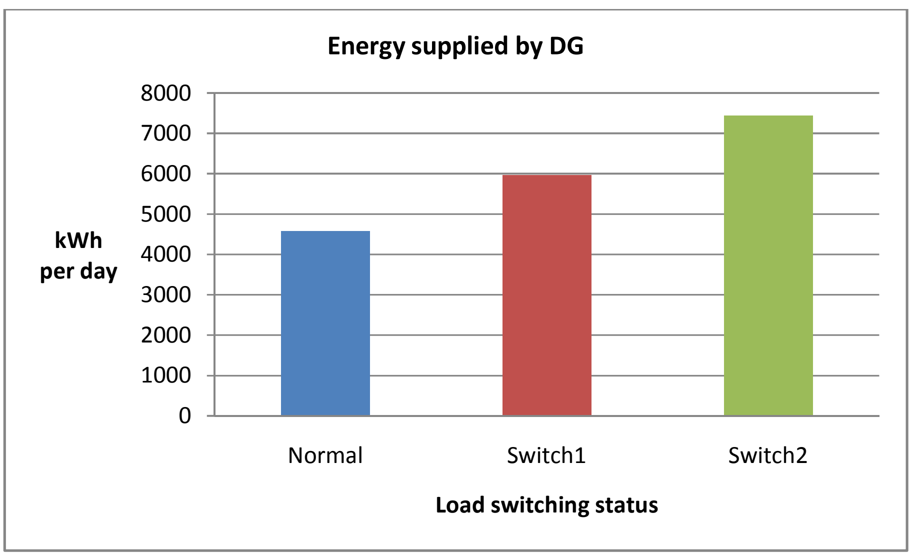


Figure 31: Energy supplied by DG on a typical day

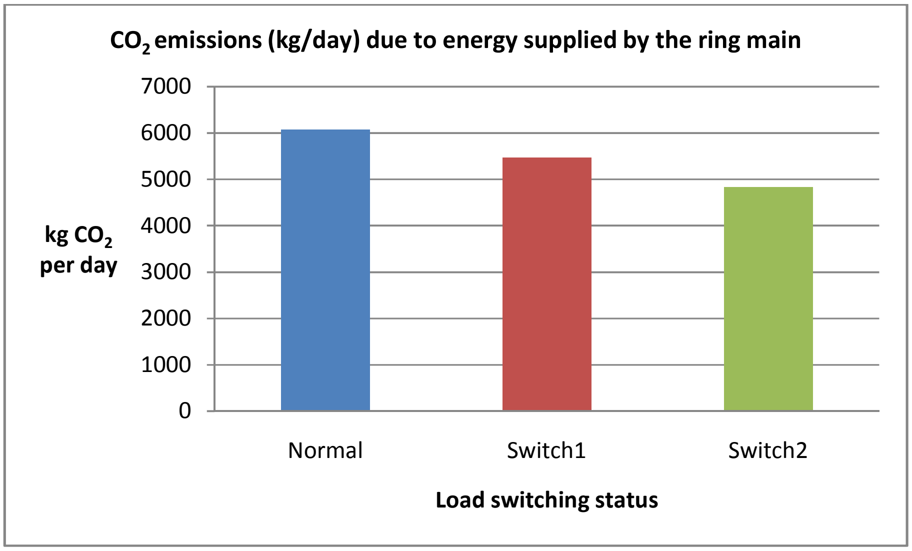


Figure 32: Associated CO_2 emissions

The above charts are representative of a typical day and can be projected to the required time interval with suitable variation factors like seasonal energy consumption differences, better equipment and efficiency of generation etc. to know the amount of energy savings and consequently cost savings and environmental benefits that are feasible. Clearly, the carbon footprint of the electricity distribution system can be reduced by such schemes considering the fact that there are hundreds of such distribution networks in the UK and they operate 24/7. Environmental benefits are two fold due to the fact that there is reduced energy consumption on the demand side and also reduced fossil fuel generation on the supply side. Thus making active network management scheme an advantageous one if implemented widely.

Active network management has consequent effects for generators, distribution operators and customers. Clearly, a number of issues, following from the different objectives of the generator and network operator, can be identified immediately.

Active Network Management issues with power generation companies:

The objective of the generator is to supply the maximum energy (kWh) to the network and so receive the largest payment [16]. Companies may have a notion that they might suffer loss of revenues due to better load management and energy sources at the distribution level. It is true to some extent that, once the energy supplied by the substations is reduced at the interval when the DG is supplying most of the load requirement as seen in some of the results in the previous section, the generation at that interval is also reduced. And there is a loss of revenue for the generating company. But considering the fact that energy demand is ever rising and the electricity networks are interconnected, all generated power will be useful at some point of the load at the given interval. Therefore loss of revenues for generation companies may not to be true for all cases. The technical issues involved are variable load requirements over a time period and hence the generator has to be controlled more frequently with distribution network management in place compared to traditional operating configuration. This may lead to increased maintenance and additional expenditure.

Issues with Distribution Network Operators (DNOs):

The objective of the DNO is to maintain supply to all customers, the majority of whom will be load customers. As the network operator has no control over the embedded generator all decisions concerning the network must be made considering the worst possible conditions of the generation for any set of network conditions. Hence at minimum (or even zero) load the maximum generation is assumed and at maximum load, minimum generation is assumed. In summary, there is no mechanism where the overall distribution network and embedded generation system can be optimised. [16]

But the DNOs have a more attractive list of advantages from active network management schemes:

- Introducing demand side management as part of ANM can postpone or avoid installation of new feeders or substations.

- Technological advancement in their operation and maintenance to meet the new trends will put the company in a better place in terms of assets and market leadership. Also helping to attract investments.
- Active voltage control allows more connection of DG and in turn generates revenues in terms of regulatory costs and operation and maintenance contracts.
- Higher level of control on the distribution network probably controlled by a central control station or by a spread of intelligent devices with communication capability.
- With DSM options, the operator is in better communication with its customers and hence will be able to operate at better load factors and make profits.

In a competitive market environment, the DNOs would have to keep their market share and promote their services for new customers to make profits and be in business. Research and development activity, either in house or derived from other organisations through sponsorships for constant improvement in technical as well as economic domains is a necessity. For example in the UK, there are different network operators in different regions and there has to be co-ordination as well as understanding between the companies to ensure smooth business by offering good customer service.

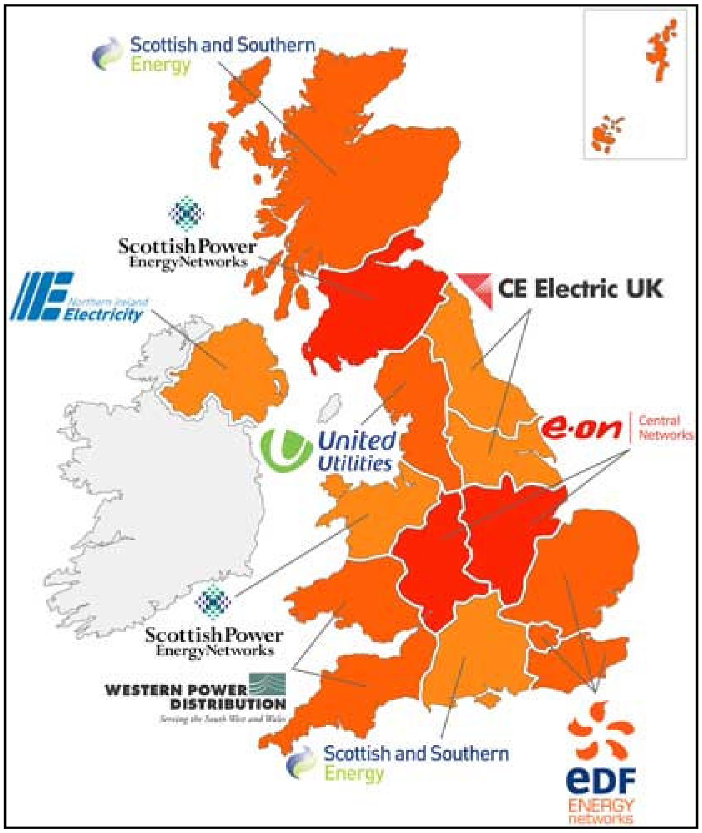


Figure 33: Distribution Network Operators in the UK

The DNO's would require some incentives from the Government as well for implementation of schemes like DSM in their operations since it has got its economic drawbacks for the network operator. Also for voltage reduction schemes due to which the revenues of the operator go down since the total energy supplied it reduced. But these incentive schemes can act as promotional or also long term in order to attract the network operating companies to implement more efficient ways of power distribution.

Issues with consumers:

Traditionally, power systems have been run on the policy that whenever the consumer demands energy this should be instantly satisfied from dispatched generation. With increasing proportions of renewable generation this philosophy must be changed but without substantial inconvenience to the consumer. Demand side flexibility will require that consumers adjust their demand profile to meet supply through deferrable loads.

This will require intelligent control and could be done through time-of-use tariffs requiring consumer voluntary response, to hard wired direct control. [10]

Active distribution control might bring some benefits to consumers in a broad sense. The fact that DNOs operate in a competitive market and maintaining network security is a primary objective makes the consumer benefit from new and efficient scheme of network management, in terms of cost and supply security. Cutting down energy bills due to load control without causing inconvenience is another benefit. Also in a social sense, the consumer can be satisfied that he is contributing in a small way to energy efficiency and indirectly the environmental benefits.

Environmental issues:

Active network management allows for connected of DG into the distribution network. If more and more renewable energy sources are used, then the overall carbon footprint of energy can be reduced. Also demand side management means more efficient use of energy and savings. In the UK context, the scheme also supports to achieve the government targets of renewable energy supply mix in the overall electricity generation and reach the target emission rates in the following decade.

Conclusion

The changing configurations of distribution networks require operational changes in terms of monitoring, control and protection. Automation of these schemes can enable efficient and easy operation and maintenance of networks. Embedded generation in the network and DSM options which help to supply the energy demand and also reduce the environmental impact due to GHG emissions become important entities of the network.

In order to control, protect and utilize them, a real time network management scheme is necessary. As a solution, active network management schemes like network voltage control and load control as discussed in this thesis help to better manage present day and future distribution networks. Load control leads to energy conservation and energy efficiency, while voltage control can allow connection of more DG on the network and energy use reduction as well.

7.2 Scope for future work

Active networks management includes many factors of distribution network operation and maintenance like control and automation, protection, load control, DG monitoring and control etc. Each topic can be dealt with detail and control or automation schemes designed using the programmable logic controller or any other microprocessor based controllers. Integrating the controller with the real time simulator enables the researcher to test the system in similar conditions as that of an actual network due to transient level simulation undertaken. Some specific suggestions of further work as continuation to this project could be the following:

- Improved load switching algorithm which control loads intelligently by monitoring network parameters.
- Improved control algorithm for voltage control with allowance for practical considerations like line drop compensation (LDC) and mechanical switching time delay for tap change operation.
- Improved communication of controller with operator or to a larger SCADA system.
- Load models can be divided into deferrable loads within the larger loads and only these deferrable loads can be switched ON/OFF by the controller.
- Intelligent devices at load centres like smart meters could be used to implement load control which can be informed by the DNO for the time and frequency of

load control. Better load monitoring is possible with such a scheme and also enables better load forecast for future control and planning decisions.

Many such improvements can be made to the control system developed in this project. And control schemes tested with simulations can be constantly improved for better performance before real world implementation.

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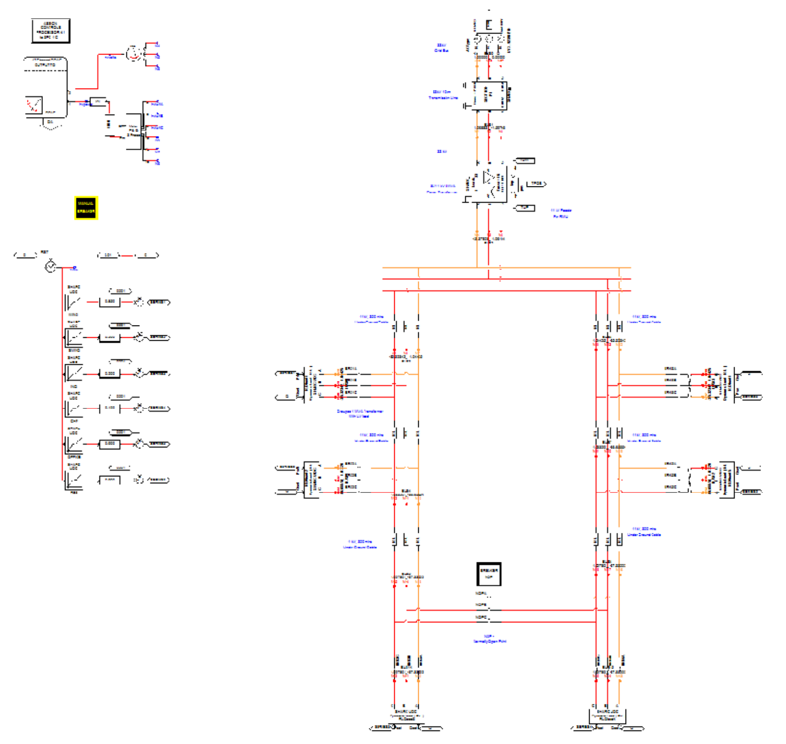
Appendix A: Network Model

The network model used for the study was created for another project in the department. However it has been modified to suit the requirements of this study. RSCAD program is used to draft the network model for later use in simulations.

A draft of the model is extracted from RSCAD and attached in this appendix for review.



RTDS Technologies	File: simple_11kV_ring Created: Jul 10, 2008 (Harsh D Ramaiya) Last Modified: Aug 15, 2008 (rtumilty) Printed On: Sep 8, 2008	Test Circuit SS #1 Subsystem #1 of 1

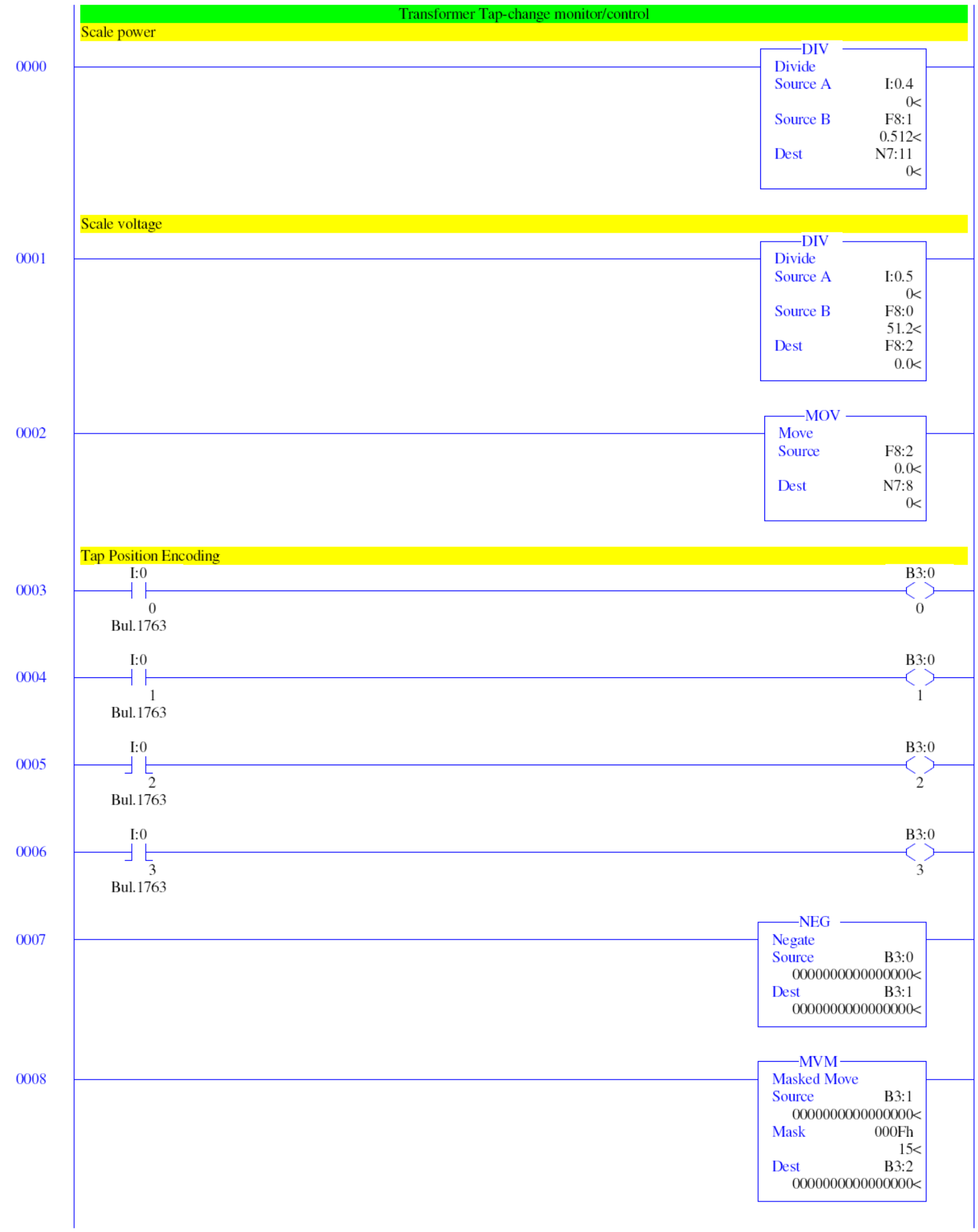
Appendix B: Micrologix 1100 product specifications

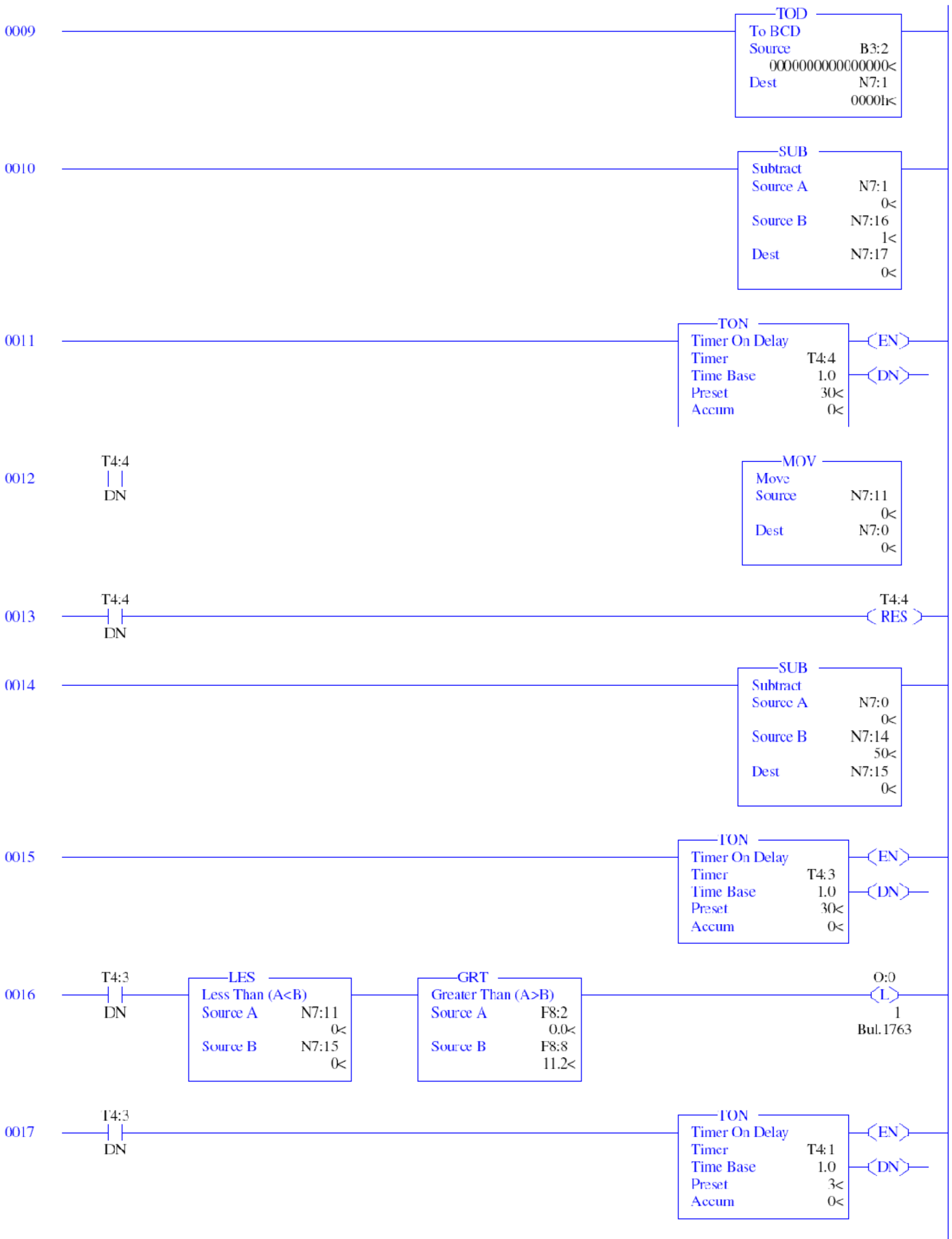
PRODUCT SPECIFICATIONS

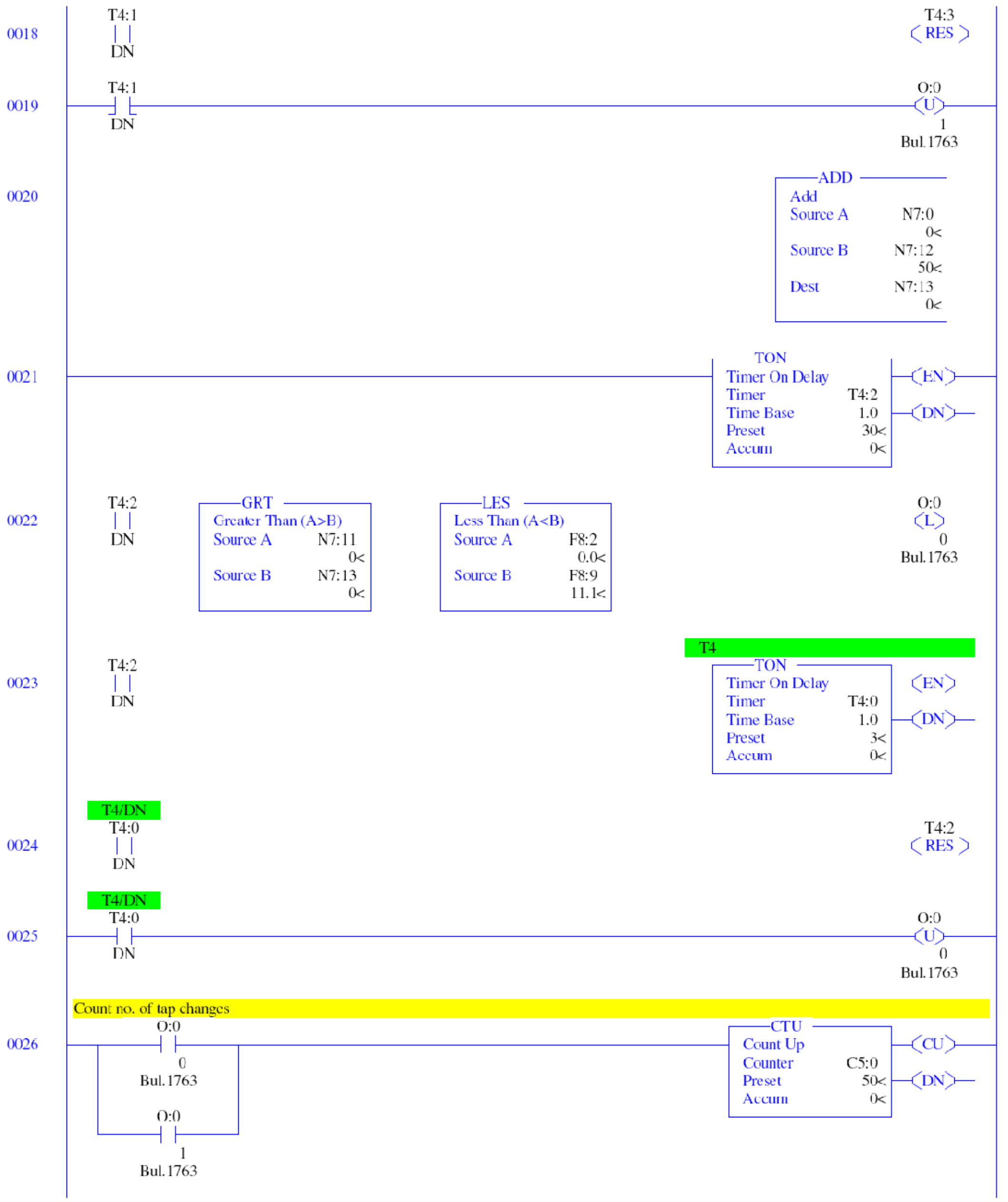
<table>
<tr><th>MicroLogix 1100</th><th>1763-L16AWA</th><th>1763-L16BWA</th><th>1763-L16BBB</th><th>1763-L16DWD</th></tr>
<tr><td>Input Power</td><td colspan="2">120/240V ac</td><td>24V dc</td><td>12V dc - 24V dc</td></tr>
<tr><td>Memory</td><td colspan="4">non-volatile battery backed RAM</td></tr>
<tr><td>User Program / User Data Space</td><td colspan="4">4K / 4K</td></tr>
<tr><td>Data Logging / Recipe Storage</td><td colspan="4">Up to 128K bytes for data logging and up to 64K bytes for recipe (recipe memory subtracted from available data logging)</td></tr>
<tr><td>Battery Back-up</td><td colspan="4">Yes</td></tr>
<tr><td>Back-up Memory Module</td><td colspan="4">Yes</td></tr>
<tr><td>Digital Inputs</td><td>Ten 120V ac</td><td colspan="2">Six 24V dc,
Four fast 24V dc</td><td>Six 12V dc / 24V dc,
Four fast 12V dc / 24V dc</td></tr>
<tr><td>Analog Inputs</td><td colspan="4">Embedded, two in local, with additional 1762 analog modules</td></tr>
<tr><td>Digital Outputs</td><td colspan="2">Six relay</td><td>Two relay,
Two 24V dc FET,
Two fast 24V dc FET</td><td>Six Relay</td></tr>
<tr><td>Serial Ports</td><td colspan="4">One RS-232 / RS-485 Combo Port</td></tr>
<tr><td>Serial Protocols</td><td colspan="4">DF1 Full Duplex, DF1 Half Duplex Master/Slave, DF1 Radio Modem, DH-485, Modbus RTU Master/Slave, ASCII</td></tr>
<tr><td>Ethernet Ports</td><td colspan="4">One 10/100 port</td></tr>
<tr><td>Ethernet Protocols</td><td colspan="4">EtherNet/IP messaging only</td></tr>
<tr><td>Trim Potentiometers</td><td colspan="4">Two digital</td></tr>
<tr><td>High-Speed Inputs
(Pulse Catch)</td><td></td><td>Four @ 40kHz input
(1ch)</td><td>Four @ 40 kHz input
(1ch)</td><td>Four @ 40 kHz input
(1ch)</td></tr>
<tr><td>Real Time Clock</td><td colspan="4">Yes (embedded)</td></tr>
<tr><td>PID</td><td colspan="4">Yes (multiple loops only limited by program and stack memory)</td></tr>
<tr><td>PWM /PTO</td><td colspan="2"></td><td>Two @ 40 kHz</td><td></td></tr>
<tr><td>Dual Axis Servo control</td><td colspan="2"></td><td>Through embedded PTO</td><td></td></tr>
<tr><td>Embedded LCD</td><td colspan="4">Yes</td></tr>
<tr><td>Floating Point Math</td><td colspan="4">Yes</td></tr>
<tr><td>Online Editing</td><td colspan="4">Yes</td></tr>
<tr><td>Operating Temperature</td><td colspan="4">-20°C to +65°C (-4°F to +149°F)</td></tr>
<tr><td>Storage Temperature</td><td colspan="4">-40°C to +85°C (-40°F to +185°F)</td></tr>
</table>

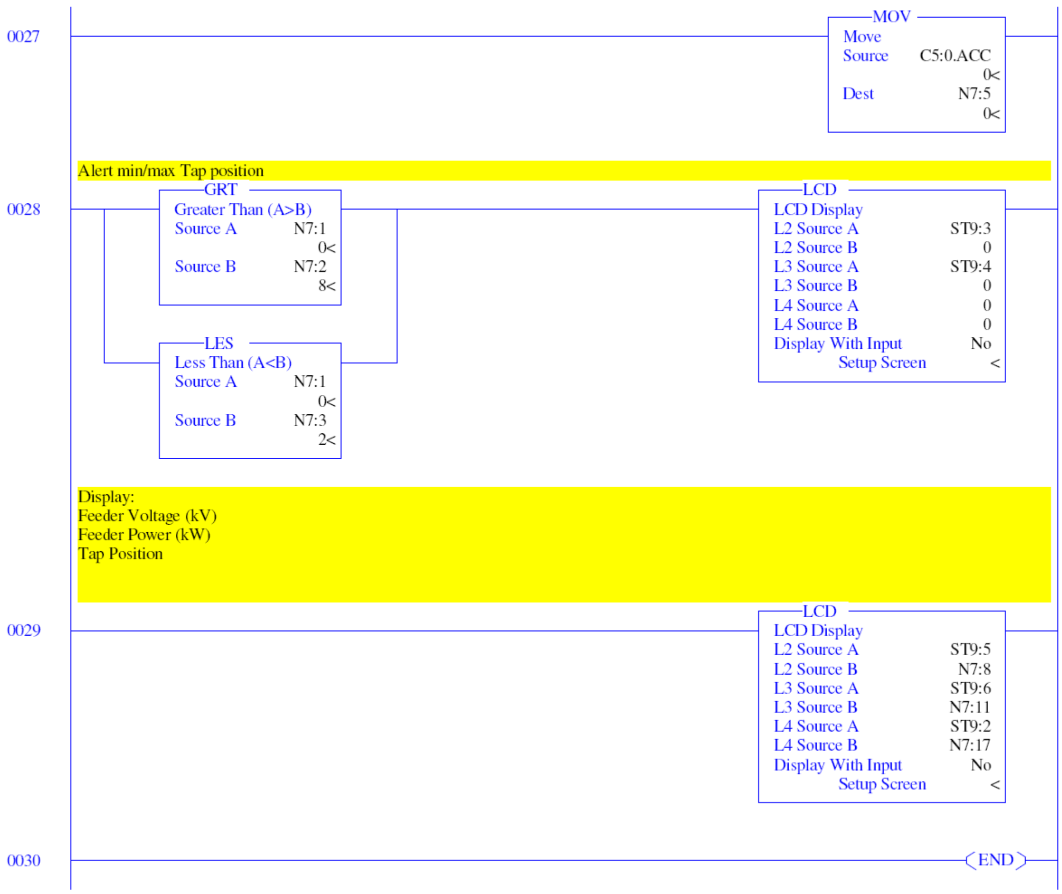
Appendix C: PLC Programming

For this project, the control system being implemented in two stages; load switching and voltage control, there are correspondingly two reports from RSLogix 500 which are attached to this thesis in this appendix. The two reports called Count1 and sequence1 respectively are the following.


Transformer Tap-change monitor/control
Scale power
0000
DIV
Divide
Source A I:0.4
0<
Source B F8:1
0.512<
Dest N7:11
0<
Scale voltage
0001
DIV
Divide
Source A I:0.5
0<
Source B F8:0
51.2<
Dest F8:2
0.0<
0002
MOV
Move
Source F8:2
0.0<
Dest N7:8
0<
Tap Position Encoding
0003
I:0
0
Bul.1763
B3:0
0
0004
I:0
1
Bul.1763
B3:0
1
0005
I:0
2
Bul.1763
B3:0
2
0006
I:0
3
Bul.1763
B3:0
3
0007
NEG
Negate
Source B3:0
0000000000000000<
Dest B3:1
0000000000000000<
0008
MVM
Masked Move
Source B3:1
0000000000000000<
Mask 000Fh
15<
Dest B3:2
0000000000000000<


0009
TOD
To BCD
Source B3:2
0000000000000000<
Dest N7:1
0000h<
0010
SUB
Subtract
Source A N7:1
0<
Source B N7:16
1<
Dest N7:17
0<
0011
TON
Timer On Delay
Timer T4:4
Time Base 1.0
Preset 30<
Accum 0<
EN
DN
0012
T4:4
DN
MOV
Move
Source N7:11
0<
Dest N7:0
0<
0013
T4:4
DN
T4:4
RES
0014
SUB
Subtract
Source A N7:0
0<
Source B N7:14
50<
Dest N7:15
0<
0015
TON
Timer On Delay
Timer T4:3
Time Base 1.0
Preset 30<
Accum 0<
EN
DN
0016
T4:3
DN
LES
Less Than (A<B)
Source A N7:11
0<
Source B N7:15
0<
GRT
Greater Than (A>B)
Source A F8:2
0.0<
Source B F8:8
11.2<
O:0
L
1
Bul.1763
0017
T4:3
DN
TON
Timer On Delay
Timer T4:1
Time Base 1.0
Preset 3<
Accum 0<
EN
DN


0018
T4:1
DN
T4:3
RES
0019
T4:1
DN
O:0
U
1
Bul.1763
0020
ADD
Add
Source A N7:0
0<
Source B N7:12
50<
Dest N7:13
0<
0021
TON
Timer On Delay
Timer T4:2
Time Base 1.0
Preset 30<
Accum 0<
EN
DN
0022
T4:2
DN
GRT
Greater Than (A>B)
Source A N7:11
0<
Source B N7:13
0<
LES
Less Than (A<B)
Source A F8:2
0.0<
Source B F8:9
11.1<
O:0
L
0
Bul.1763
0023
T4:2
DN
T4
TON
Timer On Delay
Timer T4:0
Time Base 1.0
Preset 3<
Accum 0<
EN
DN
0024
T4/DN
T4:0
DN
T4:2
RES
0025
T4/DN
T4:0
DN
O:0
U
0
Bul.1763
Count no. of tap changes
0026
O:0
0
Bul.1763
O:0
1
Bul.1763
CTU
Count Up
Counter C5:0
Preset 50<
Accum 0<
CU
DN


0027
MOV
Move
Source C5:0.ACC
0<
Dest N7:5
0<
Alert min/max Tap position
0028
GRT
Greater Than (A>B)
Source A N7:1
0<
Source B N7:2
8<
LES
Less Than (A<B)
Source A N7:1
0<
Source B N7:3
2<
LCD
LCD Display
L2 Source A ST9:3
L2 Source B 0
L3 Source A ST9:4
L3 Source B 0
L4 Source A 0
L4 Source B 0
Display With Input No
Setup Screen <
Display:
Feeder Voltage (kV)
Feeder Power (kW)
Tap Position
0029
LCD
LCD Display
L2 Source A ST9:5
L2 Source B N7:8
L3 Source A ST9:6
L3 Source B N7:11
L4 Source A ST9:2
L4 Source B N7:17
Display With Input No
Setup Screen <
0030
END

SEQUENCE1

LAD 2 - --- Total Rungs in File = 9