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Issues for connection of distributed generation in rural/remote power systems

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ISSUES FOR CONNECTION OF DISTRIBUTED GENERATION IN RURAL/REMOTE POWER SYSTEMS

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Abstract

Connection of distributed generation (DG) into a distribution grid system affects the normal operation, control and protection of the distribution system. This paper addresses some of the technical issues arisen due to the addition of generation to a rural/remote distribution network. In this paper, a voltage controlled rotary DG is modelled to operate in the line of voltage sensitivity for maximum voltage improvement. A scenario-based study on DG operation and control has been conducted and recommendations for effective operation of DG presented. An investigation on barriers to inclusion of utility owned and customer owned DG has been carried out and methods of addressing these recommended. Barriers to DG connection can be minimised with proper planning, technology selection and design. Community DG benefits may be promoted to overcome any regulatory objections.

1. INTRODUCTION

A system with DG has greater load carrying capacity and can correct for poor voltage profile, especially needed in rural areas and during peak time of the day. However, with the aim of effective integration of DG into utilities' networks, several requirements, such as voltage regulation, loss of main protection and the sustainability of DG following disturbances on the associated network, need to be satisfied. The use of DG provides such benefits as improving power quality, reducing the requirement for central generating station reserve, and for reactive power support [1]. In addition, grid supported DG release transmission capacities, reduce network losses, and avoid or postpone network upgrades of high investment costs.

The introduction of DG sources can significantly impact the power-flow and voltages at customer sites and utility equipment [2]. Selecting DG technology depends on various factors such as locations, customer demands, generation requirements, connection requirements, financial investments and returns, and the environment. With low penetration of DGs, the system impact might be negligible. But as the penetration level increases the impact becomes significant. The authors of [3] have proposed a new voltage regulation coordination method to coordinate DGs with tap changers and line drop compensators. In [4], the authors have attempted to determine DG impact on Australian rural lines and explored voltage control and line protection issues in the presence of DG. Authors in [5] have ascertained net sensitivity and impact on existing protection of single wire earth return (SWER) lines due to DG inclusion. In [6], operation and control of DG based on a synchronous generator have been discussed and dynamic interaction between tap changers and DG is investigated.

In this paper, potential technical issues related to DG connection in rural/remote areas have been explored. A rotary DG is modelled based on voltage sensitivity of lines to support voltage profile of the distribution feeders. A survey is carried out to explore the overall operation and control strategies of DG, connected to the utility grid system. Barriers to the connection of DG into distribution grid systems have been examined and guidelines to overcome these have been suggested.

2. MODELLING OF A RURAL/REMOTE POWER SYSTEM WITH DG

A rural/remote distribution grid typically comprises of transformer, regulator or tap changer, ACR (automatic circuit recloser), feeder, sub feeder and loads. The main supply at the connection of the distribution feeder is modelled by its Thevenin equivalent. The Thevenin voltage is assumed the same as the substation voltage and Thevnin impedance is obtained from short-circuit MVA level at that point. Uniform load distribution is assumed for the entire feeder.

An equivalent model of tap changers is derived by determining the turns ratio of each tap changer effect at every point of the feeder and using this to modify voltages, currents and impedances for individual points of the feeder. The derived model represents the equivalent turns ratio at each point of the feeder and is used to observe the effect of tap changers on the system voltage due to the change of tap position of the individual regulator. The tap changer varies the tap position based on the voltage level at its secondary.

The rotating synchronous machine type of DG is used in this study. DG is modelled as a voltage source and a constant impedance. Synchronous machine DG is characterised by low inertia, high reactance, short-time constant and poor inherent damping. In this modelling of DG, an artificial damper is used to suppress any oscillation. As rural systems are usually rated for loads in the hundreds of kVA, smaller sizes of rotary DGs (approximately 100kVA or less) are investigated in this study. All loads are represented by a constant admittance model, uniformly distributed in the feeders. Load dynamics are not modelled in this study. Lines are modelled using the short-transmission line approximation due to the short length of line segments.

3. CONTROL STRATEGY OF DG

A control strategy of a DG of rotary type can be developed from the concept that fuel injection will produce real power and field excitation will produce reactive power from a DG [6]. A proportional plus integral (P-I) control with low-pass filter may be employed for the design of DG controller. The following equation gives an indication how the voltage error controlled by P-I controller.

$$C = K_P\left(V_{actual} - V_{reference}\right) + K_I \int \left(V_{actual} - V_{reference}\right) \quad (1)$$

where, V_{actual} and $V_{reference}$ are the actual voltage of DG connection and pre-specified reference voltage to be achieved by DG, respectively. K_P and K_I are the proportional and integral constants, respectively. C is the controller-generated signal.

The DG should be operated at the line of voltage sensitivity for maximum voltage improvement. At the connection point of DG, voltage sensitivity analysis is required to be performed to determine the optimal operating point of DG. Voltage sensitivity at this point can be observed by injecting maximum amount of real and reactive power from a small DG, individually. By applying equation (2), the ratio of voltage sensitivity to real and reactive injection for a given distribution system can be determined. The sensitivity ratio of the system is used to calculate the operating point of DG.

$$SR_{DG} = \frac{\partial V / \partial P}{\partial V / \partial Q} \quad (2)$$

At steady-state condition,

$$P = SR_{DG} Q \quad (3)$$

The maximum value of real power "P" generation at a given sensitivity is,

$$P_{\max} = \frac{SR_{DG}}{\sqrt{1 + SR_{DG}^2}} \times DG_{size} \quad (4)$$

where, SR_{DG} is the ratio of sensitivity of voltage to real power and reactive power of DG and DG_{size} is the rating of the DG.

4. SOLUTION OF NETWORK EQUATIONS

The network is assumed to consist of N buses, and the network admittance matrix $[Y_T]$ formed from the network parameters is of size of N×N. From the concept of reduced bus matrix and equation $[Y_T][V_{bus}]=[I_{bus}]$, the network solution is obtained. For the case of DG inclusion, an additional node is required for the internal voltage for each DG and the network admittance matrix is modified accordingly to obtain the network solution. DG voltage magnitude and angle are calculated from DG field excitation and input power, and DG controller is used to update them according to the voltage level at the point of DG connection to the network.

5. SIMULATION RESULTS

A prototype distribution system is derived from electricity network of rural areas in Western Queensland. Simulations are conducted on the test system using MATLAB 6.0. A 120-km rural network has been modelled with line resistance of 1.828 Ω/km and line reactance of 0.876 Ω/km. An OLTC transformer with voltage regulation facility is connected at the beginning of system. For this test system, the regulator is connected at a distance of 12km from the source. The high source impedance of the system requires the regulation to be closer to the source [7]. 100 kVA single DG of rotary type has been installed on the backbone feeder to investigate the voltage improvement. The maximum voltage drop allowed in distribution systems is 6% [7].

Fig.1 shows the voltage profile with fixed tap set at the nominal transformer ratio. The maximum amount of load for this condition is found as 184 kW. Load power factor is assumed 0.8 lagging and kept constant in all cases. The delay time for tap operation is limited to 5 sec.

DG is operated to generate both real and reactive powers to support voltage and load of the system. The voltage sensitivity of lines is calculated and found to be 1.8:1. It is used to calculate the operating point of DG and DG controller generates real and reactive powers in the direction of voltage sensitivity for effective operation and voltage support. Fig.2 shows voltage profile for maximum load of 480kW with DG. At this load, DG generates maximum DG current shown in Fig.3 and maximum power of 100kVA. The changes of tap positions to support the network voltage with 480kW load are shown in Fig.4. In this case, the loading capacity and voltage profile of the network have been improved appreciably.

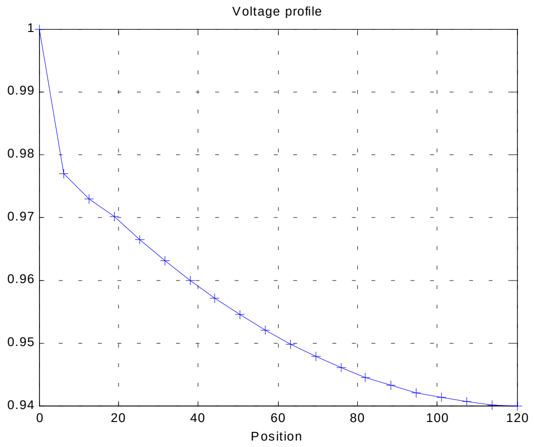

Fig.1: Voltage profile with 184 kW load and fixed tap of nominal ratio (Voltage in p.u. and Position in km).

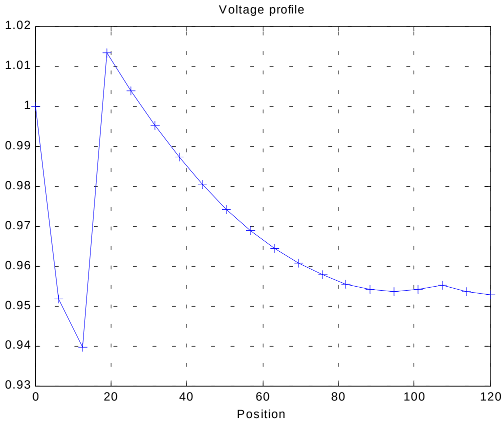

Fig.2: Voltage profile with maximum 480 kW load and 100kVA DG (Voltage in p.u. and Position in km)

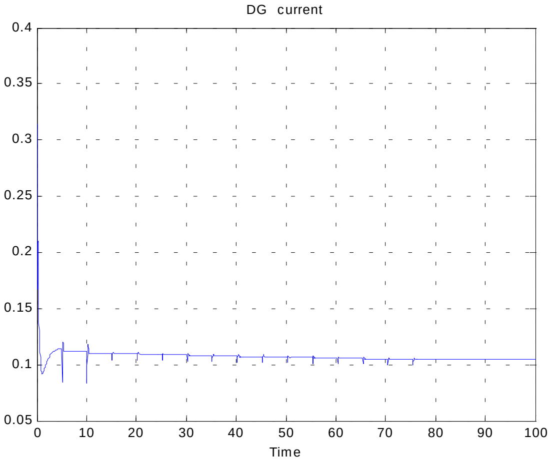

Fig.3: DG current to support maximum 480 kW load (Current in p.u. and Time in Sec.)

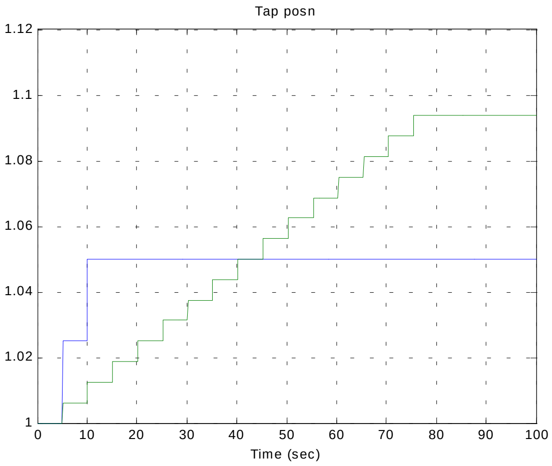

Fig.4: Tap position to support maximum 480 kW load with DG (Voltage in p.u.)

6. SCENARIOS FOR DG CONNECTED WITH DISTRIBUTION GRID SYSTEM

The following scenarios are considered to determine the suitable operation and control scheme:

(i) net input of DG with local load (Resort); (ii) DG with local load and power export to Grid; (iii) net export with intertrip, and (iv) multiple generators with start penalty.

6.1 Scenario One: Net input of DG (500kVA-5MVA) with Local load (tourist area) Operating in Parallel with MV Utility Network

Description of scenario: 1MVA DG is connected to 11kV grid system and dedicated for local load in a tourist area. The size of DG just matches the peak demand of resort load.

Operation and Control: DG will run continuously to fulfil the real power demand of the local customer. DG may be switched on or off depending upon the net generation, and also the amount of local customer’s load switch connected. If the local demand is less than a minimum preset value, DG will be turn off and the customer demand (less than the preset value) will be fulfilled by utility grid. If the demand exceeds the preset value for a certain time (say 15 minutes), the distributed generator will start running automatically to satisfy the required demand.

6.2 Scenario Two: DG (500kVA-5MVA) with Local load and Power Export to the MV Grid System

Description of scenario: 3 MVA DG is connected to 11kV grid system and dedicated for local load and exporting to grid. The peak demand of local load is set at 2MVA.

Operation and Control: DG will be switched on or off depending upon the voltage level. Protective equipment (over/under voltage relays) must ensure that the voltage produced by the DG stays within ±10% of the rated voltage, under all circumstances [8]. If the voltage strays outside the limits, the DG must be tripped off. DG will generate maximum real power during peak time. DG may be switched off during off-peak and utility must be capable to support the customer-demands at that time.

Limit to DG operation: It is not recommended to operate DG for a few minutes/ short periods as it involves starting, synchronising and stopping cost and time for every operation. The operating time may be predicted by studying the demand profile of the customers and utility power availability in the grid. But DG must be able to run at any time. For low diversity DG may need to run from line measurements.

6.3 Scenario Three: Net Export with Intertrip

Description of Scenario-A: A small DG is connected to 11kV bus of utility grid system at which an industrial load is connected. The size of DG is smaller than the industrial load demand. The utility intertie breaker is also connected to the same bus. The control of the generation is tied to the operation of the protection breaker.

Communication and control link: Communication and control links should be established from grid intertie breaker to DG breaker to trip DG breaker off when inter tie circuit breaker trip off and avoid islanding. It must ensure that DG breaker will trip off when loss of grid system occurs in the utility network.

Description of Scenario-B: A DG is connected to 11kV bus of utility grid system at which a remote load is connected. The size of DG just matches the peak demand of remote load. The utility intertie breaker is also connected to the same 11kV bus.

Communication and control link: Communication and control links should be established from grid intertie breaker to DG breaker to signal DG about the loss of main grid. In this situation, DG and the local load will island and DG will generate the necessary power to fulfil local load demand. While DG is in idle situation and the grid system fails to supply power to the remote load, the communication and control link will prompt the DG to switch on automatically to fulfil the local demand.

Operation and Control of Scenarios A and B: Same as Scenario Two described in Section 6.2.

6.4 Scenario Four: Multiple Generators with Start Penalty

Description of scenario: Multiple DGs with various DG technologies (Diesel, Gas turbine, PV, Fuel cell, etc.) are connected at different points of 11kV rural radial network to support the network. These generators are controlled through the SCADA system.

Control and communication: A communication and control scheme will be developed from distribution substation to all distributed generators. Smart controller (designed for automated distribution system with various controlled strategies) or intelligent computer in distribution substation may monitor and control all DGs' activities through communication and control links. DG will be switched on or off depending upon the net generation and voltage level monitored by SCADA. The load profile will be observed all the time at the control station. If there is a sudden increase in load demand somewhere in the distribution network, the immediate decision to operate DG (near the increased load) or increase net output of DG will be taken to fulfil the excess demand. Protective equipment (over/under voltage relays) must ensure that the voltage produced by the DG stays within ±10% of the rated voltage, under all circumstances [8]. If the voltage strays outside the limits, the DG must be tripped off.

Start Penalty: To start and run a DG efficiently depends on its technology. For immediate start of a DG requires its immediate power output at rated voltage and frequency. PV technology is good for immediate start-stop operation, as it is capable to generate power instantaneously. But synchronous generator requires few minutes to run before connecting to the network, for synchronisation with the network and network loads during starting. As DG is usually called upon to start after a minimum delay from the instance of actual need to run, the slow-start technologies may delay further to fulfil customers' demands. Another drawback of these technologies is that they create a transient over-voltage when they are switched onto network. Whereas, PV and Fuel cell can be switched on at the instance of zero voltage crossing which reduces power quality problems. If there are many DG technologies existed in the network and there is a need to start DGs for immediate power generation, the sequence to start the technologies may be followed as PV, Fuel cell, Gas turbine, and Diesel. However, different DG technologies are generally installed at different places, far from each other. In that case, the portion of the network is suffering the voltage dip severely, DG existed in that portion or nearby may be called upon to start immediately to boost the voltage level. If the DG technologies are designed to start-up by following the voltage constraint, then DG, which will see the voltage level equal to or lower than the lower voltage constraint first, will start immediately and other technologies will follow the same criteria. As all the technologies do not normally start at the same time of the day, DG technology start can be chosen based on the requirement and amount of power generation, peak-shaving, demand fluctuations, efficiency and starting time of technologies, duration of run, etc. Some technologies are not suitable for frequent start-stop and short-duration of run, for example Diesel and Gas turbine. In these situations, they will not run efficiently. These technologies are suitable to operate for few hours continuously. These DG technologies will operate optimally if they are allowed to run at full load for long time (not less than an hour). PV and Fuel cell are suitable to operate for frequent start-stop and short time if their starting costs are neglected.

7. ISSUES TO BE ADDRESSED FOR CONNECTION OF DG INTO THE SYSTEM

DG offers energy management opportunities and the potential to reduce overall losses. Power quality and reliability can be increased at the presence of DG. Also, waste heat from DG can be processed for domestic needs if the DG is installed in a domestic area. However, the main technical limitations of DG inclusion into distribution networks are fault level, voltage control, load flows and capacity, configuration and network security.

The roles of Distribution Operators in controlling the active network [9] will be increased in real-time studies, state estimation, power-flow control, voltage control, security assessment, power quality assessment, DG and network stability management, outage co-ordination, constraints management, fault level control, system recovery and restoration, island operation if designed, and system access facilitation.

7.1 Barriers to Utility Owned DG Implementation at Rural/Remote Areas

DG at rural/remote areas has a greater possibility for becoming separated, as the failure rate of utility supply is high in these areas. Therefore, anti-islanding protection will be a very important part of protection system. Utility owned DG might face the following potential barriers during implementation at rural/remote areas.

- Potentially longer time required for investment-return because of low customer revenue on rural feeders
- Lack of communication infrastructure, especially for resynchronisation
- Lack of standard equipment for automatic DG operation, control and protection (including anti-islanding or islanding)
- Potentially long repair time particularly for equipment needing specialist skills
- The distance of the DG from the system operation centre will add extra difficulties for monitoring and response for equipment failure
- Lack of standards and commercial practices for interconnection
- Regulatory issues and authority approval for generation ownership
- Maintenance of power quality if running an island isolated from the grid.

7.2 Benefits of DG Ownership to Network Utilities

Potential DG benefits for utilities are as follows:

- The deferral or avoidance of T&D upgrades.
- Reductions in line losses during peak periods.
- The ability to mitigate shifts in demand quickly, without making long-term investments.
- New infrastructure capacity can be added incrementally-when and as needed.
- Local and/or system-wide utility service reliability may increase.
- New products and services may be provided, such as premium quality power, green energy, thermal energy, and back-up power or high reliability electric service.

7.3 Barriers to Customer Owned DG Implementation

Barriers to DG implementation include interconnection requirements, electric rate structure, supplemental rate structure, competition transition charges, utility status and siting/permitting [9]. The largest barrier is the lack of interconnection standards. Interconnection charges by the utility may negate the savings incurred by the DG unit. A Utility may charge a fixed monthly rate and only a nominal usage fee, which will reduce per kWh charge and remove incentives for DG operation. Charges must reflect actual connection costs – not theoretical and the charges must be differentiated by technology. The structure must accommodate both, peak shaving (predictable usage), and inter-operable systems. The use of DG will support the peak power demands, provide critical customer loads with emergency stand-by power, improve user power quality, and provide low-cost total energy. Potential barriers to customer owned DG can be summarised as below [9]:

- Large initial investment requirement.
- Lack of standardized interconnection requirements.
- Certification requirements of equipment.
- Net Metering – lack of “fair” price on power delivered to the grid.
- Utility status – how DG owners/operators are licensed and liable for power quality if isolated from the grid.
- Siting and Permitting and meeting environmental impact requirement can add significantly to project cost.

7.4 Suggestions to Overcome the Barriers for Customer DG

The following are the suggestions to overcome or mitigate customer DG barriers:

- adopting uniform technical standards for interconnecting DG to the grid,
- adopting testing and certification procedures for interconnection equipment,
- accelerating development of DG control technology and systems,
- adopting standard commercial practices for any required utility review of interconnection,
- establishing standard business terms for interconnection agreements,
- developing tools for utilities to assess the value and impact of DG at any point on the grid,
- developing new regulatory principles compatible with DG choices in both competitive and utility markets,
- adopting regulatory tariffs and utility incentives to fit the new DG model,
- establishing expedited dispute resolution processes for DG project proposals, and
- defining the conditions necessary for a right to interconnect.

8. CONCLUSIONS

Effects of DG connection into utility grid systems have been investigated in this study. A scheme of voltage sensitivity based DG operation is presented to correct the network voltage efficiently by DG. Protection scheme for DG connection has been discussed. Scenario based case studies are conducted for (i) net input of DG with local load (tourist area), (ii) DG with local load and power export to Grid, (iii) net export with intertrip, and (iv) multiple generators with start penalty; and control schemes for DG operation are suggested. Barriers to DG connections have been addressed for utility owned and customer owned DG separately, and guidelines have been suggested to overcome the barriers. DG benefits and outcomes from DG installation are presented, which can be used as a tool to address some of the DG barriers.

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