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Fault Analysis of Predictive Based Static Compensator in Microgrids

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Abstract

Microgrid composes of distributed energy resources (DER), storage devices and controllable loads. Microgrids are the infiltrations center for the non conventional energy resources, backup and management of distribution units. This paper describes the transient behavior of a Low voltage Microgrid which works in an Isolated and Grid connected mode of operation. Predictive control algorithm is implemented in the operation of the Microgrid along with Distribution Static Compensator (DSTSATCOM). Reactive power and Harmonic compensation is possible with Model Predictive (MPC) Based Distribution Static Compensator. Isolated mode is analyzed separately. Different types of Faults are being simulated with MATLAB/Simulink software platform.

Keywords: Microgrids, Non-Conventional Energy, Model Predictive Control, Power Quality, Reactive Power.

INTRODUCTION

In traditional low voltage grid, the energy is supplied to the loads top to bottom from the central power station. The loading has increased with boost up the power quality and reliability problems. The power quality problems are due to the presence of mainly the non-linear loads and the power electronic converters at the load side for supplying DC power to the special loads. The omnipresence of power electronic devices in the loads, generators and Grids that causes the power quality issues which should be reduced. The advancement in the increased use of energy which enhance the usage of distributed energy resources, have paved the way to the implementation of new technologies to connect these resources. This increased the importance of power quality in the concept of Distributed Generation.

Distributed generation is otherwise called as onsite generation with low voltage grids. It is connected directly to the consumer side with a rating below 50MW. This generation consists of different renewable energy resources connected to the load by means of converters. The complete structure of energy resources and loads with converters are connected to the main grid via a static switch. This concept is otherwise called as Microgrid. The technology in distributed energy resources consists of wind, solar, microturbine reciprocating turbines etc. The energy storage devices like batteries fly cells and supercapacitors also constitute apart from the energy resources. The above technologies together with storage devices perform coordinated control over the network operation. Microgrid systems are interconnected to the medium voltage network and can be operated Islanded in case of faults in the grid connected network. Microgrids provide support in times of accentuation by removing congestion and alleviate restoration after faults. Thermal and Electricity needs are provided from customer point of view and in addition, improve reliability, reduce emissions, enhance power quality and possibly, lower costs of electrical energy.

The capability of Microgrids to operate in islanded mode can possibly relive the effects of faults in the challenging network. In order to isolate external faults and provide stability in autonomous operation, Microgrids require the capability of sophisticated protection, control and communication framework.

This paper outlines the transient stability of the Microgrid with three resources and battery storage in both Grid connected and Islanded modes of operation. Each DER is modeled with the help of model predictive controller (MPC). The provision of custom power devices (CPD) like Static compensator (STATCOM), Unified power flow conditioner (UPFC) etc also supplies signals that compensate reactive power and Harmonics by line compensation. The insertion of passive filters of specific values also gives the compensation in case of faults. The proposed Microgrid is analyzed with different types of faults like three phase faults, Line to ground and Double line to ground faults.

In Islanded mode of operation, an incorporated model is been suggested. The model is reviewed with the faults after the Grid is disconnected from the Microgrid. The passive filters are an important alternative to compensate the current and voltage disturbances in the Microgrid. The filters are also analyzed with the faults.

This paper presents a control strategy to improve the power quality in a Microgrid. The attention will be mainly focused on the fault analysis of the Model Predictive Based Distribution Static Compensator which allows injecting energy to the Microgrid, compensating the current harmonics and supplies voltage at the point of common coupling. The validity is proved through many simulation tests using Simpower Systems from MATLAB.

PROPOSED MICROGRID

In this section a model of a typical Microgrid with fault is explained that was used to carry out the analysis of the power quality issues. A typical Microgrid is shown in Figure 1.

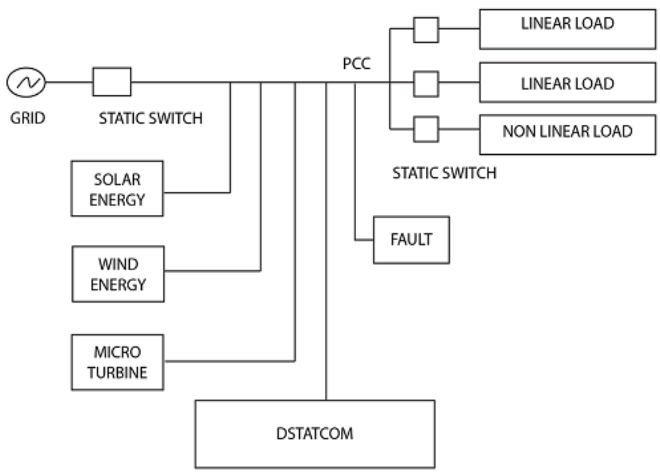

Figure 1: Proposed Microgrid model

In the proposed Microgrid diagram, three distributed energy resources blocks like Solar Energy, Wind Energy and Microturbine are modeled in both Grid connected and Isolated modes of operation. It is then connected to two linear and non-linear loads via a static switch. Linear loads like Incandescent lamps, Heaters etc and the Non- linear loads are SMPS, Refrigerators, Television etc. The static switch is closed in grid connected and opened in islanded mode. The compensation of reactive power and harmonics is done by Model Predictive Controller (MPC). Each Distributed resources are modeled with the Predictive algorithm separately and added to the point of common coupling.

Distribution static compensator is also added to the PCC by modeling with Model Predictive Controller. The transient behavior of the model is done with three phase fault. The fault is added to increase the transient stability of the Microgrid with the proposed predictive technique. The fault analysis is done in both grid connected and isolated mode of operation.

A DSTACOM is a custom power device which is utilized to eliminate the harmonics from the source currents and also balance them in addition to providing reactive power compensation to improve the power factor or regulate the load bus voltage. With the shunt connected controllers (DSTATCOM), it is possible to control the power flow in critical lines. DSTATCOM was also modeled with the Predictive Controller to regulate the power flow at the point of common coupling. The system was checked with the two modes of operation and using fault analysis mode too. The effectiveness of the proposed system was verified using the MATLAB/SIMULNK program

BRIEF REVIEW OF PREDICTIVE CONTROL

Model predictive control also referred as Receding Horizon Control or Moving Horizon Control has shown to respond in an effective way on these demands in many practical process control applications and is therefore widely accepted in process industry. Standard Predictive Controller optimizes the Microgrid operations over a planning horizon to fulfill a time varying demand, subject to operational constraints while minimizing a cost function. An open loop sequence is computed with step by step control MPC algorithm for the optimization of future behavior. The first control action in the optimal sequence is applied and the entire optimization is repeated at further control steps. An explicit dynamic model is been used to predict the future reactions of the manipulated variables and the control signal that is obtained by minimizing the cost function. The illustration of principle of predictive control is Figure.2.

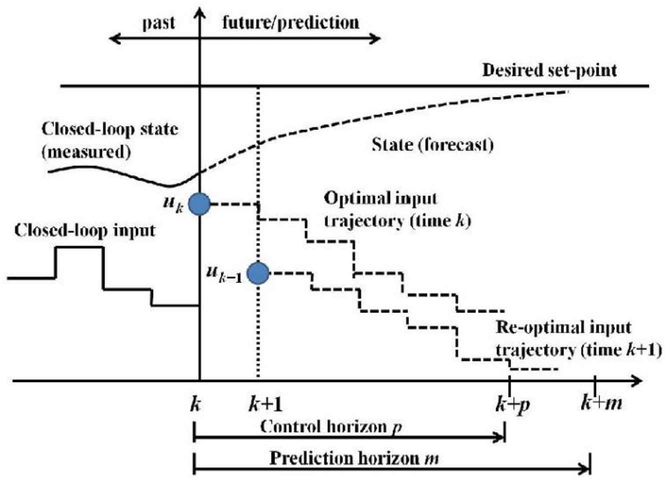

Figure 2: Principle of Predictive Control

MPC contains the following three ideas,

1. A model is used to predict the process output along a future time horizon.

2. The calculation of performance index optimization with control sequence.
3. A receding horizon method in which horizon is moved towards the future, which involves the application of the first control signal of the sequence calculated at each step.

The formulation of a nonlinear discrete system with MPC control is characterized by

$$X_{K\_+1} = f(x_k, u_k, v_k)$$

$$Y_k = g(x_k) + w_k$$

where $\boldsymbol{x_k}$ a vector of state variables is, $\boldsymbol{u_k}$ is a vector of controls, $\boldsymbol{Y_k}$ a vector of outputs or controlled variables, $\boldsymbol{v_k}$ and $\boldsymbol{w_k}$ are the noise or disturbance vectors. The complication with the computation in sequence of controls $\{\boldsymbol{u_k}\}$ (k=0 ……N_c –1) that will take the system from its current state $\boldsymbol{x_k}$ to a desired state $\boldsymbol{x_s}$ **.** The desired steady state **(x, u, y)** is either fixed or determined by a steady state optimization. In the last case, it can be computed either once for all or at each time step.

The Predictive control algorithm can be explained with the help of a block diagram shown in figure 3. The control diagram is applicable to two modes of operation of the proposed Microgrid. The predicted outputs from the Model are added to the reference trajectory and errors are designed and given to the optimizer and the feedback is sent to the process. The system Model is having the input from optimizer and the output from the process control block. The Optimizer consists of minimum cost function and constraints with parameters which gives the optimum Predicted outputs. The constraints can be disturbances or noises.

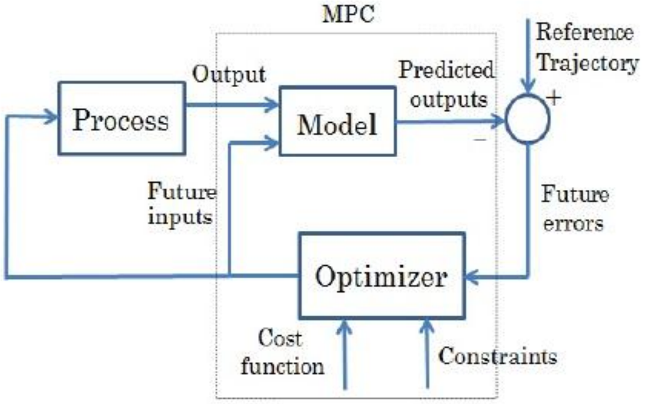

Figure 3: Block diagram of MPC algorithm

The Predictive algorithm consists of minimizing the objective function, which is described by:

$$\text{Min}_z \quad \sum_{K=0}^{N-1} ||y_{t+k} - r(t)||^2 + \rho||u_t + K||^2$$

Subject to constraints

$$X_{t+k+1} = f(x_{t+k}, u_{t+k})$$

$$Y_{t+k} = g(x_{t+k})$$

$$u_{min} \leq u_{t+k} \leq u_{max}$$

$$y_{min} \leq Y_{t+k} \leq y_{max}$$

$$x_t = x(t),\ k=0\ldots\ldots N_c\text{-}1$$

The two terms in the objective function focus at penalizing future deviations of outputs from the desired steady state over the prediction horizon T_P ($N_p=T_p/\Delta t$), future deviations of controls from the desired steady state over the control horizon T_C ($N_c = T_c/\Delta t$) and future rapid changes in controls respectively. The weighting matrices and the bounds have been assumed constant for simplicity.

The effective implementation of predictive control needs the following issues to be handled:

1. *System Model*: System linearization is usually considered to make the problem tractable and accurate.
2. *Sampling time, prediction and control horizons:* The sampling interval fundamentally depends on the system dynamics. The system settling time is to be covered by taking the prediction horizon large enough. The control horizon is usually taken smaller than prediction horizon and renders the number of possible controls. In order to achieve the desired performance in the closed loop and while in stability, long horizons are taken rather than small horizons.
3. *Optimization method:* The linearized system model and the objective function results in the formation of highly convex Quadratic Programming (QP) problem optimization. Several standard solution algorithms and codes are available for this problem.

PREDICTIVE BASED DISTRIBUTED STATIC COMPENSATOR

DSTATCOM is employed at the distribution level of the Microgrid for the power factor improvement and the voltage regulation. Additionally, a DSTATCOM can also behave as a shunt filter to eliminate unbalance or distortions in the source current in the both modes of operation. It is a multifunctional device and the main objective of the control method should be to make it flexible and easy to implement in addition to exploit its functionality to the maximum.

The control algorithm used in the DSTATCOM modeling is Predictive Control Technique (MPC). The compensation of reactive power and harmonics is also done by this method. Each Distributed resources are modeled with the Predictive algorithm separately and added to the point of common coupling. Only the first step of the control strategy is implemented, then the model state is sampled again and new calculations are repeated starting from the new current state, yielding new control & predicted path. MPC starts adjusting the control signal head of the reference changes.

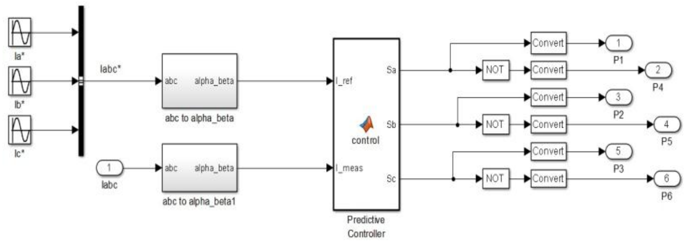

Figure 4: Predictive control in DSTATCOM

MPC controller is shown in figure 4. The reference currents to the DSTATCOM is produced by the MPC by the help of three reference signal constants converted to alpha-beta version and is given to the Predictive control block from the Simulink tool box. Actual currents are also sensed and given to the controller block. Controlled output signals will be fed to the PCC from each modeled Distributed resources. In the predictive control block the reference values and the measured values i.e. the current state of the system taken as input. The Reference is termed as I_Ref and Current state is termed as I_mean. The Load parameters such as resistance Inductance and voltage is taken arbitrarily.

A number of seven states are considered from V_0 to V_7 with initial and final values are taken as zero. In the Receding Horizon method, the different states are taken as below,

$$V_1 = \frac{2}{3} * V_{dc} \text{ -----} \quad (1)$$

$$V_2 = \frac{1}{3} * V_{dc} + 1j * \frac{sqrt(3)}{3} * V_{dc} \text{ ----} \quad (2)$$

$$V_3 = -\frac{1}{3} * V_{dc} + 1j * \frac{sqrt(3)}{3} * V_{dc} \text{ ------} \quad (3)$$

$$V_4 = -\frac{2}{3} * V_{dc} \text{--------------------------} \quad (4)$$

$$V_5 = -\frac{1}{3} * V_{dc} + 1j * \frac{sqrt(3)}{3} * V_{dc} \text{----------------} \quad (5)$$

$$V_6 = \frac{1}{3} * V_{dc} + 1j * \frac{sqrt(3)}{3} * V_{dc} \text{ ---------------} \quad (6)$$

The equations of the state V_1 and V_4 are the complex conjugates and also V_2, V_3 and V_5 , V_6 are also the conjugates with the measured values of dc voltage. These states form a matrix which is given below.

$$V = [V_0, V_1, V_2, V_3, V_4, V_5, V_6, V_7]$$

In the next condition reference current values at the sampling time K which is the current instant is taken into consideration and it is given by the equation

$$i_{k_{ref}} = I_{ref(1)} + 1j * I_{ref(2)}$$

The measured current values are taken at the same sampling time K and the current state at K^{th} time is given by the equation,

$$i_k = I\_mean(1) + 1j * I\_mean(2)$$

Then the estimation of back emf is governed by the formula

$$e = \left[V(x_{old}) - \frac{L}{T_s} * i_k - \left(R - \frac{L}{T_s}\right) * i_{old} \right]$$

$$[\, x_{old} = 1 \;\&\; i_{old} = (0 + j0)]$$

The measured current value is taken for the next iteration

$$i_{old} = i_k \; [present\ state]$$

The value of ***I*** varies from 0 to k+1 and V_01= V(i). The predicted current value at the k+1 instant is given by the equation,

$$i_{k1} = \left(1 - R * \frac{T_S}{L}\right) * i_k + \frac{T_S}{L(V_{01} - e)}$$

Where V_01 is the voltage at the next state

e represents the emf function calculated earlier.

The cost function of the respective system/device which is tyrannized by an equation is given below,

$$\mathrm{G} = \mathrm{abs}(\mathrm{real}(\mathrm{ik}_{\mathrm{ref}} - \mathrm{i}_{\mathrm{k1}})) + \mathrm{abs}(\mathrm{img}(\mathrm{i}_{\mathrm{kref}} - \mathrm{i}_{\mathrm{k1}}))$$

Where **abs** represents the absolute of the value after the calculation with the sum of the real and imaginary terms of the reference and measured values. The cost function depends on the constraints

$$g < g\_opt)$$

$$g_{opt} = g$$

$$x_{opt} = i$$

The optimum value is stored in **X_old** and the optimum switching states are been selected from the equations given below,

$$S_a = state\ (x_{opt}, 1)$$

$$S_b = state\ (x_{opt}, 2)$$

$$S_c = state\ (x_{opt}, 3)$$

The optimum value is predicted and the switching states are given to the inverters as pulses at the gate terminal. With these pulses the DSTATCOM will inject voltages and currents to the point of common coupling. The Model predictive controller predicts the optimum values for the proper function of the devices and helps in the modeling of distributed energy resources in the Microgrid. In the emergency conditions or in the isolated mode where the voltages undergo unacceptable deviations from their reference values or even become unstable in the case of transient conditions, the objective remains the same but high speed and magnitude of actions are needed. The main benefit of MPC in isolated transient conditions is the coordinated control of the all controls working under stress and system is close to or outside its normal limits making the control task even daintier. The reaction time of an MPC based control ranges from say 10 to 60 seconds, when long term dynamics are concerned. The technique used above in the prediction reduces the complexity of the resulting model and hence contribute the computational efficiency required to fit the constraints of an online application. In normal operating conditions of the Microgrid reference voltages and currents are taken from the Grid and it is possibly a delicate task for adjusting numerous controls.

RESULTS & DISCUSSIONS

The Simulink diagram for the transient response of the proposed Microgrid model is shown in the figure 5.

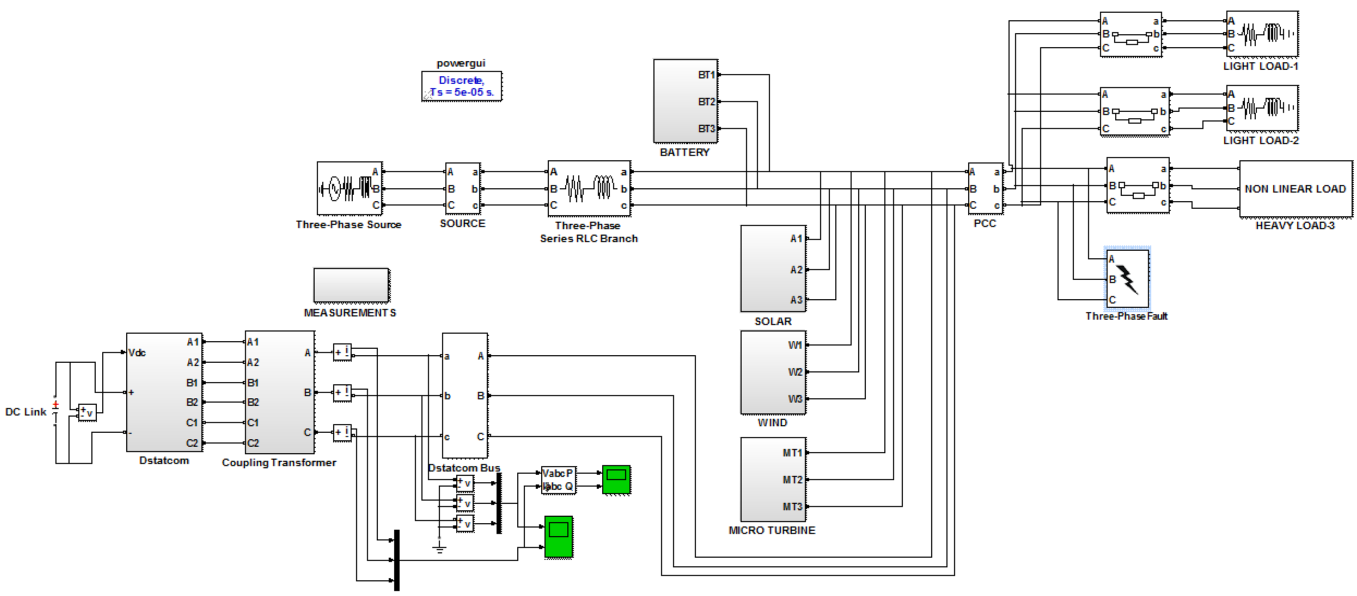

Figure 5: Simulink diagram of proposed model

The test model contains three Distributed energy resources which are modeled with the Predictive controller and the power ratings of the solar and wind models with a varying output of 5kW and reactive power of 10kW varying with respect to time. Three loads are connected to the PCC with two light loads of 25 kW each and a non linear load of 18 kW with 8.5KVAR and 12.3 KVAR respectively. The grid rating is 2500 x10^6 VA and 60 Hz frequency. The model performs the two modes of operation 1) Grid connected mode 2) isolated mode.

In the test model a three phase fault is added at 0.5 sec and 0.7sec. In both modes of operation the stability is been analyzed. In grid connected mode the inoculation of fault is been compensated by the distributed energy resources and the Grid with the help of DSTATCOM and the predictive technique. The presence of linear or non linear loads doesn't make any difference in the output. The output in Grid connected mode with three faults is shown below.

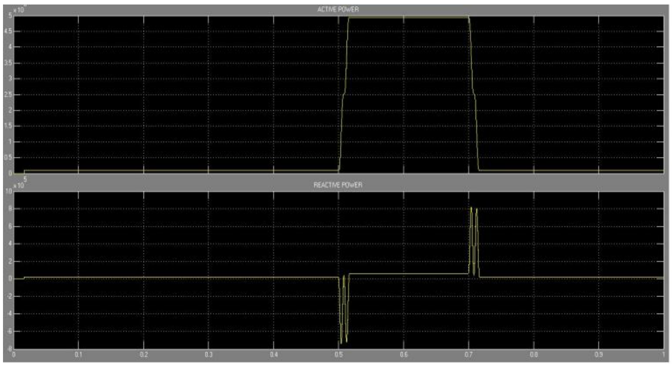

Figure 6: Single line to ground fault

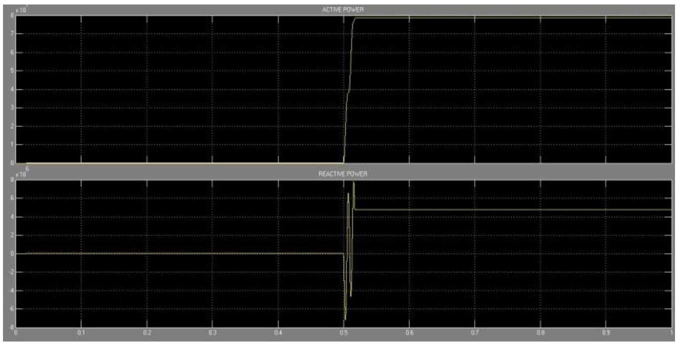

Figure 7: Double line to ground fault

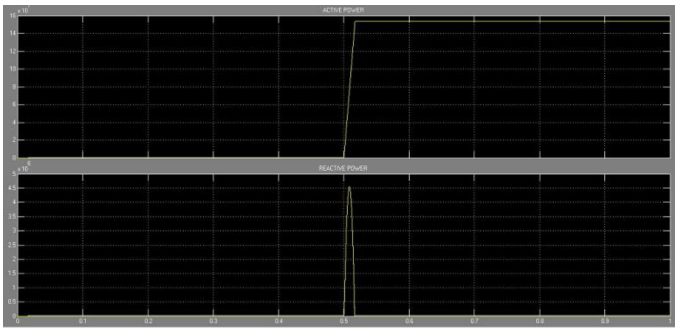

Figure 8: Three phase fault

In the figures 6, 7 & 8, Fault occurs at 0.5sec and 0.7sec. Slight deflection in waveform can be seen in the active and reactive power at loads. An active power of 5kW, 8 kW and 16 kW are produced in the output waveform after the occurrence of faults. The reactive power is compensated at -8kVAr to +8kVAr. The transient behavior is been analyzed in the grid connected mode of operation with three faults and their compensation with the help of the predictive control technique.

In Isolated mode of operation, same faults are given to the Isolated model with one linear and one non- linear load. The incorporated model of the proposed Microgrid system is shown below,

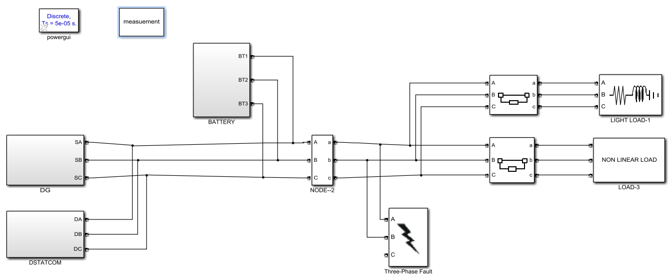

Figure 9: Isolated model

The output at the load is after the fault is shown in the figures below,

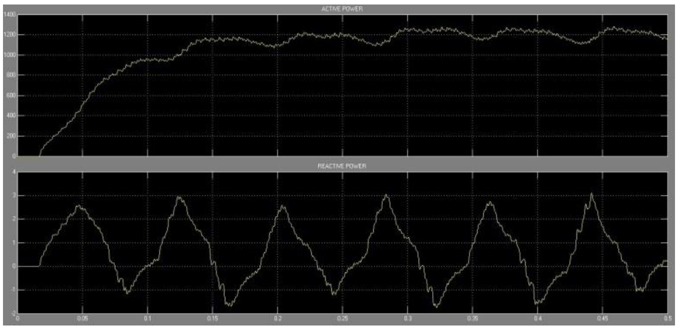

Figure 10: Single line to ground fault

Slight distortions are seen in the active power as well as the reactive power output at the loads. The reactive power is compensated and the value varies between -3kVAr and +3kVAr. In this mode of operation distributed resources alone with the help of SOFC battery is feeding power to the linear as well as non-linear loads. The double line to ground fault and three phase fault waveforms are shown in 11 & 12.

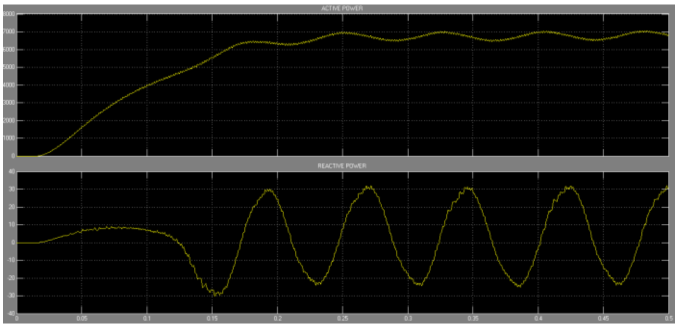

Figure 11: Double line to ground fault

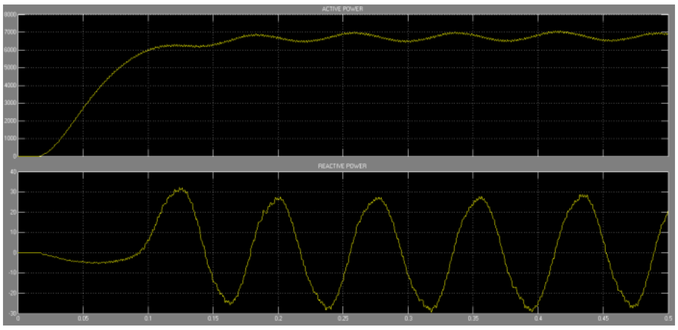

Figure 12: Three phase fault

In the isolated mode, complete mitigation of the harmonics and the distortion is possible with the help of passive filters. A capacitive filter of value 1500 micro farad is added to the test system after the DSTATCOM and the incorporated model with one side grounded. The output at the load is completely free from distortion. Negative reactive power is caused by capacitive loads that include lighting ballasts, variable speed drives for motors, computer equipment, and inverters.

CONCLUSION

Fault analysis was done in the Microgrid with the help of MPC based DSTATCOM. The transient stability of the Microgrid and the compensation of the reactive power were examined with the simulation results. Predictive controller was successfully implemented in the Distributed resources and the power quality issues with the help of faults were studied, analyzed and compensated in the proposed Microgrid. MPC based DSTATCOM was incorporated in the Microgrid and comparative results were done in both Grid connected and Islanded modes with the help of Simulation. The control algorithm that helps in the modeling of DGs and the Static compensator was explained. In Grid-connected mode, DGs compensates the non-linear and unbalanced loads and shares with utility grid in a pre specified ratio. During islanded mode, on basis of the future analysis advantage characteristics and the variations of voltage and frequency, an automatically power sharing among DGs ensures the stable operation of Microgrid and the smooth transformation between two modes. Battery source was also added to the Microgrid to compensate the loads in the islanded mode. The validity of the control algorithm and the proposed Microgrid is been examined with MATLAB. A comparative study of the transient behavior with conventional PI controllers and the fuzzy logic controllers was done and MPC offers good improvement in transient stability.

APPENDIX

DC VOLTAGE	400V
SWITCH FREQUENCY	16Hz
GRID VOLTAGE	400kV, 2500MVA
VOLTAGE IN ISLAND	390kV, 60Hz
LIGHT LOAD1	25kW ,8.5kVAr
LIGHT LOAD2	25kW, 10kVAr
NONLINEAR LOAD	18kW , 12.3kVAr
X/R RATIO	10
V_{dc}	450 V (Vary)

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