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Model Predictive Control Strategies for Low-Voltage Microgrids

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Modern concepts for grids are being developed owing to the increasing stress put on the electrical producers and the burgeoning need for thermal demands due to varying climate conditions. The increasing awareness of the depletion of natural resources has also been a driver in the direction of modern grids which are more efficient and less susceptible to failures. One solution which is being considered as an alternative for the existing centralised electrical grid and thermal needs is the concept of microgrid.
Microgrids are decentralised subunits which consist of different cogeneration units and combined heat and power units along with renewable sources and heat and electricity consumers. Multiple microgrids combine together to aid and complement the existing producers thus, reducing the stress on these producers while increasing the efficiency of the entire electricity grid. The presence of different storage devices and electricity production units mean that the microgrids can also maintain very high quality of electricity, thus reducing losses during transmission and distribution. Another advantage of a microgrid is it's ability of being self-sufficient for a short period time which means that microgrids have the ability to island themselves voluntarily or accidentally from the rest of the electricity grid which could be used to prevent entire grid failures during meteorological problems or when the economic factors are not conducive.
The presence of decentralised sources, storage devices and consumers mean that there is a strong need for control of all the different components that constitute a microgrid. There are many different approaches to control a microgrid.
This paper attempts to demonstrate a model predictive control (MPC) strategy developed to provide strategies for a low-voltage microgrid with both thermal and electrical devices and requirements. The aim of the strategy is to satisfy the demands and comforts of the consumers while minimising the costs associated by performing a multi-layered mixed-integer optimisation which provides strategy that needs to be employed by each unit of the system. The optimisation consists of two layers, the first of which provides the setpoints for both the thermal and electrical components and the second layer solves a problem which is only takes the electrical units into account and is performed over a shorter timestep. This is owing to the different dynamics of the thermal and electrical units. The fast dynamics of the electrical systems requires us to perform the second layer to maintain the efficiency of the microgrid.
The paper then shows the importance of optimal sizing for the model predictive control strategy employed for varying periods of the year and the advantages of this strategy for microgrids over the existing strategies. The paper also attempts to show the impact of certain variables employed in the MPC strategy in particular, for LV (Low-Voltage) microgrid.

1. Introduction

With the rising demand for electricity and heat owing to climate change, development of nations and more applications which use electricity, the existing centralised grids are being pushed to its limits and so are the use of the resources. With this in mind, newer technologies and alternatives are being studied to

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replace the existing grids. Grids that will prevent failures, ensures better efficiency and ensures the comfort of the user.

Modern grids unlike the existing unidirectional centralised grids would follow the template of a decentralised bidirectional grid where the marked delineation between producer and consumer is markedly blurred. There are many ways to ensure all the above mentioned factors can be ensured. Weber (2006) and Fazlollahi (2012) show us the importance of optimizing the different components involved in the system for maximisation of the comforts and satisfaction of the demands. But, even after the optimisation, to ensure the demands are satisfied, techniques like Demand Side Management (DSM) and forecasting are required for proper supply of the electricity and heat demands. This necessitates the need for new methods to control to prevent failures in the grid and to maintain the efficiency of the grid and the safety of the different users in the grid and how they interact with the rest of the users in the grid as has been demonstrated in works like Kriett (2012). There are different ways of dealing with it, as has been shown by Lasseter (2002). Model Predictive Control has been one of the more promising forms of control as has been shown in Menon (2013) which has been proposed for the control of modern grids. This paper aims to show an alternate methodology for sizing for a system integrated with model predictive control designed especially for microgrids. The details are provided in the following sections.

1.1 Microgrid

Microgrids are as the name suggests, smaller grids which can be used to satisfy the demands of the local users in the microgrids while interacting with the entire grid and acting exactly like a component of the entire grid. On the other hand, microgrids has the marked advantage over the existing grid in that they are able to island themselves either voluntarily or for safety purposes and still function for short durations. They are also able to integrate distributed loads like renewable sources much better. This means that in case of low electrical quality or unfavourable grid prices, the microgrid could be disconnected to maintain the entire grid efficiency and/or save money for both the consumers and the producers.

Micrograds can be implemented at various levels, depending on the power and the voltages that they fall into. Various benchmarks have been set up for this purpose by IEEE for high voltage, medium voltage and low-voltage grids. But, the fact that the microgrids have so many different elements mean that microgrids need to have multiple sources of management and control for maintaining the quality as can be seen in Lasseter (2002) using various voltage controls and controls for maintaining the electric power quality and satisfaction of the demands. For the purpose of satisfying the electric and thermal demands and to provide set-points for the production units, this paper uses model predictive control.

1.2 Model Predictive Control

Model Predictive control is a very useful and well-developed control approach that has been used for various purposes of automation of different industries, mainly the petroleum industry and other refining industries as can be seen in (Bakosova, 2013). It is nowadays, being used to solve the problems that are being posed in the implementation of smart grids and power management. There are different ways of implementing model predictive control or MPC. But, fundamentally all predictive control strategies involve solving an optimisation problem over a limited time horizon. This paper follows the studies conducted by Collazos (2009) and (Menon, 2013) and improves on it through the implementation of a Model Predictive control which involves the solving of a Mixed-Integer Linear Programming (MILP) model of the grid in question. Further details are given in the methodology section.

2. Methodology

The initial model predictive control model was based on work done by (Collazos, 2009). The model predictive control consists of different subunits which are used to create a 24-h strategy with a 1-h time step. Each hour of the day, the strategy is recalculated for the coming 24-h which is the horizon. The MPC provides set-points for the electricity and heat demands for the residences for the next coming hours, while simultaneously providing the set-points for the switching on or off of the units in the microgrid. Thus, the inputs into the first part is the external temperature at starting point and the state of the different components of the system at start, and the outputs are the power requirements from each unit and the variables for switching on and off of the units. The set-points for the units are provided by integral variables. It is for this purpose that the MPC involves solving a MILP problem.

The system in consideration is of vital importance here. Most studies conducted until now solely use arbitrary or abstract concepts of the system in question and the external grid. For the purpose of this paper, a Low Voltage Microgrid has been chosen. The reason a LV microgrid has been chosen is because, this represents the typical end-user level grid for apartments, residential consumers and suburbs. Thus, studying a LV microgrid makes it a good choice to represent the residential and commercial sectors. The LV microgrid chosen is a benchmark set up by the IEEE CIGRE committee set-up for the purpose of defining benchmarks solely for microgrids. This means that if the MPC is able to provide strategies for the benchmark, it becomes apparent that the it could be applied to a real microgrid, as the benchmark used by IEEE is the industry standard for electrical grids. The benchmark in question has been shown in Figure 1 and the values of the impedances and all the units in question have been retrieved from Papathanassiou (2005).

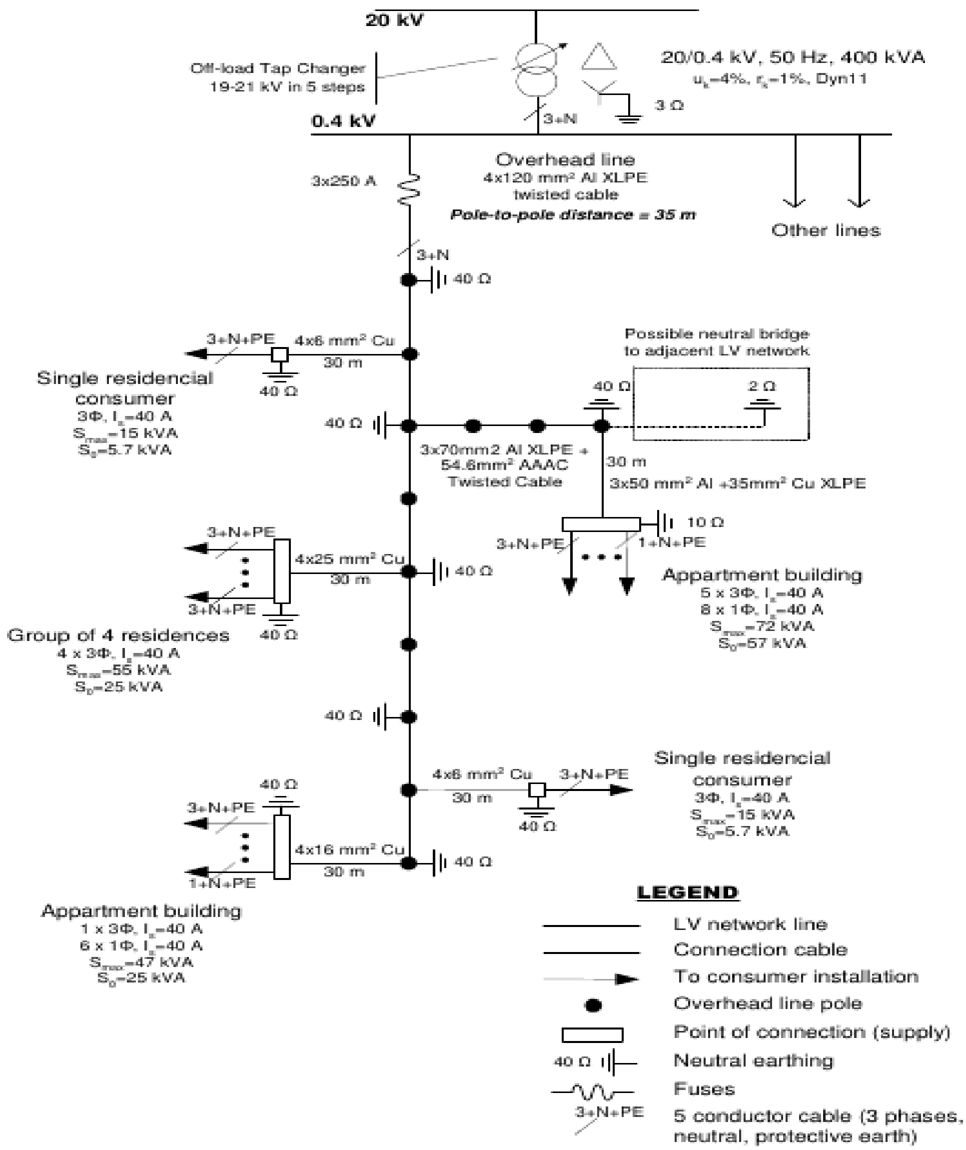

Figure 1: CIGRE benchmark used for LV-microgrid for the model predictive control

Prior to the implementation of the MPC on the system, the units have to be optimally sized, this is done using the methodology outlined by Molyneaux (2010) using the basic MPC equations added as constraints to the multi-objective optimisation. The size of the units in the grid were used as decision variables and a pareto curve was drawn from which the user can select the optimal sizes of the units depending on the results for various typical days and extreme days that were considered (4 typical d and 2 extreme d were considered).

The MPC involves solving a multi-level MILP problem. MILP is a common method employed for optimisation of problems where integral variables are required for the units as in Haikarainen (2013). There are two levels to the MPC. The first level involves solving the 24-h horizon with the 1-h timestep to create electricity and thermal demands for users while keeping in mind the constraints on accepting or providing electricity from/to the microgrid to/from the external grid. These particular variables are quite important as these can be set as either constants or variables which can be modified or treated as decision variables of their own. This means that the MPC could be used to modify the behaviour of the storage devices and the cogeneration devices to either accept or provide electricity from/to the external grid at will to satisfy the grid demands. The electrical prices used are the day-ahead market electricity prices as the interactions are at grid level. The solution of the problem also provides the set-points for the distributed energy systems through the integer variables for the coming one hour.

The second level of the MPC involves solely the electrical interactions. This second level is in place owing to the difference in inertia between the electrical and thermal flows. The electrical flow interactions are solved using a Newton-Raphson method that has been linearised for ease of calculation and the electrical flows are optimised by keeping to the power quality regulations for the grid. This solution is used to update the electrical and heat demands every 15 min. At the end of the first hour, the strategy is recalculated with a new 24-h horizon and this is repeated for the entire day. Both of the levels have been encoded in Python and the solver used for solving the problem is CPLEX.

Eq(1) depicts the multi-objective sizing problem summarized in the form of one equation where OPC is the Operating cost, INVC is the Investment cost and TC is the Total Cost. Eq(2) shows the top level of the MPC strategy, Eq(3) shows the Newton-Raphson method and the correction involved between the scheduled real and complex part of the power and the calculated electrical power components. P and Q are the real and complex parts of the electrical power and J is the langrangian matrix of these components. Eqs(4) and (5) depict the four variables (ψ, ψ',χ, χ') that have been added to limit or adjust the amount of electric power that can be stored as thermal or electric storage or provide to the external grid at any moment with SOC being the state of charge of the storage at any point and y_{cg} being the binary integer variable making sure whether the cogeneration or heating units are switched on or not. All the other major equations used in the calculation for the optimal sizing and MPC strategy have already been listed in Menon (2013), the unit models from (Girardin, 2010) and multi-objective optimisation from Molyneaux, (2010).

$$min_{Q_n, y_n}\left[OPC+INVC,CO_2\right]s.t.min_{Q_{n,t}, y_{n,t}} TC \tag{1}$$

$$min_{Q_n, y_n}\left[OPC\right] where n=unit \wedge t=time \tag{2}$$

$$\Delta P = P_{i,sch} - P_{i,calc}\,;\ \Delta Q = Q_{i,sch} - Q_{i,calc}\,;\begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix}.\frac{\begin{pmatrix} \Delta\delta_2 \\ . \\ \Delta\delta_n \end{pmatrix}}{\begin{bmatrix} \frac{\Delta(V_2)}{(V_2)} \\ . \\ \frac{\Delta(V_n)}{(V_n)} \end{bmatrix}} = \frac{\begin{pmatrix} \Delta P_2 \\ . \\ \Delta P_n \end{pmatrix}}{\begin{bmatrix} \Delta Q_2 \\ . \\ \Delta Q_n \end{bmatrix}} \tag{3}$$

$$\Psi'\left((1-SOC).\dot{E}l_{st} + C_t\right) \le \dot{E}l_{give}(t) \le \chi'\left((1-y_{cg})\dot{E}l_{cg} + (1-SOC).\dot{E}l_{st} + C_t\right) \tag{4}$$

$$\Psi\left(y_{cg.}\dot{E}l_{cg} + SOC.\dot{E}l_{st}\right) \le \quad \dot{E}l_{accept}(t) \le \quad \chi\left(\dot{E}l_{cg} + SOC.\dot{E}l_{st}\right) \tag{5}$$

3. Results

The sizing was performed for various buildings that can be seen in the microgrid figure. The buildings used are based on the SIA standards, which are the Swiss architectural standards. The buildings used as the target for the different units were predominantly Multiple Family Houses (MFHs) and Single Family Houses (SFHs). The single family houses replace the single residential consumers and the bigger residences are replaced by MFHs. The units attached are displayed in Table 1. The heat pump models have been modelled as described in Girardin (2010). The electric storage models are based on basic SOC (state of charge) models of electrical batteries. The sizing was performed by using the Multi-Objective Optimisation tool to minimise the total cost, the operating cost and maximising the emission savings, while using the sizes of the various units as the decision variables for the different typical days and the most appropriate sizes were chosen based on the pareto curves that were created.

Then using the optimal sizes and using the impedance values for the microgrid collected from (Papathanassiou, 2005), the MPC was used and run for various days of the year, especially for different seasons and with different variables of transfer. The transfer variables mentioned in Eqs(4) and (5) were modified for the same days and the same buildings. Figure 2a and b show the effect that change of the variable responsible for ability to accept electricity from the grid was modified from 0.8 to 0.5. The house that has been taken as the case of study for the figures was a single family house fitted with a cogeneration engine and thermal storage. The error bars on top of the bar graphs in Figure 2a and 2b shows the amount of electricity that could be accepted or given to the external grid. Figure 2a for the 9th hour have a substantial ability to accept electricity from the grid. On the other hand, upon the change of the variable to 0.5, now the microgrid is incapable of accepting the same amounts as can be seen in the figure. This also brings about a change in the strategy employed for the satisfaction of the electrical demands as can be seen for the same 3 hours of the day. The change in the variable brings about a more substantial use of the cogeneration engine which as a result fills up the storage device. This makes it difficult for the house to accept electricity from the grid or from the cogeneration engine.

Table 1: Buildings and units studied for the microgrid

SFH 1	MFH 1	MFH 2	MFH 3	SFH 2
Stirling Engine Thermal Storage	PEM Fuel Cell Thermal Electric Storage	Air-Air Heat Pump +Thermal Storage	Heat Pump Thermal Electric Storage	Stirling engine+Boiler +Thermal Storage

Similar studies conducted for the entire grid with the different buildings mentioned above shows the efficacy and the ability of the microgrid to provide and stick to strategies that could be used to satisfy the electrical and thermal demand of all the users in the grid, while successfully integrating distributed energy resources. This not only raises the efficiency of the grid, but also saves the cost of production and provides the user with substantial savings over a year. The grid is also able to be an active agent in shifting the peaks that are created during daily consumption of electricity and heat in the residential and commercial sector, thus reducing the wastage of fuel resources and also improving the stability of the grid in general.

(a) (b)

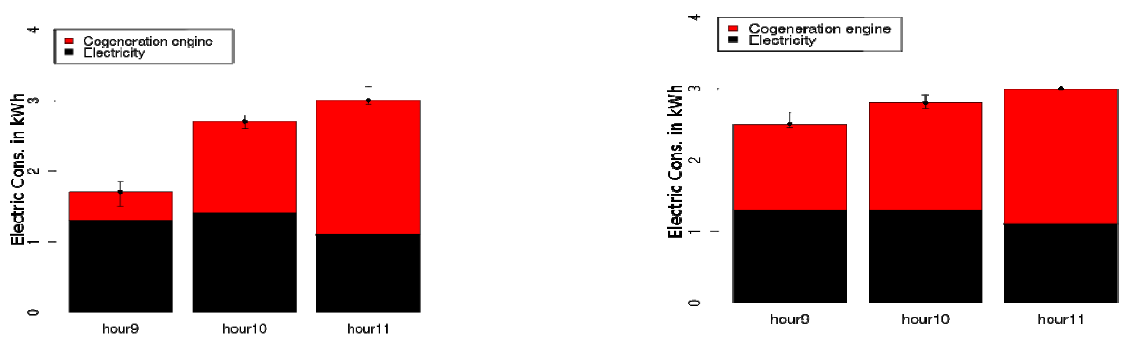

Figure 2 a)and 2 b): Fig.2a on the left shows the strategy created for a single-family house with transfer variable at 0.8 and Fig.2b on the right shows the strategy for the same house when the variable is reduced to 0.5

4. Conclusions

Microgrids are one of the new concepts towards the transition from the existing electrical grid and thermal demand to a decentralised grid that would be able to satisfy the electric and thermal demands of the users in the microgrid. The paper shows a methodology to optimally size the units involved in satisfying those demands including thermal and electrical storage devices, cogeneration units and heat pumps. It also shows the advantage of the use of the variables that have been implemented to improve the ability of the microgrid to supply or accept electricity from the external grid at any point of time. The paper uses a benchmark to study instead of an abstract concept of the microgrid for better ability to integrate with the existing infrastructure and the improvement due to the new variables and the predictive control can be observed in the strategies and the ability of the grid to better supply or accept electricity and store it in the storage devices.

Model predictive control is thus, shown to be a very potent method to control and device strategies for users in a microgrid and satisfy both the electrical and thermal demand in the grid. This opens up the possibility of better integrating and bringing in smart grids much sooner than expected. This also means that with the use of concepts like microgrids and model predictive controls, the efficiency of the grid, user comforts and safety of the grid can be better guaranteed.

There is more work being done on the validation of the sizing and the MPC strategy on a microgrid test-bed being developed in tandem with the MPC itself. The microgrid setup being developed is a complete representation of the grid and consists of all the electrical and thermal components and electrical, thermal and mass storage devices. The validation results will be published in another paper in the near future.

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