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Non linear Predictive Control Strategy for Standalone DC Microgrids

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***Abstract*—Microgrids are becoming a way of integrating renewable energies, lowering costs and providing better grid quality all around the world. Energy Management Strategies (EMSs) are becoming essential for the power sharing purpose and regulating the microgrids voltage. The classical EMSs track the Maximum Power Points (MPPs) of wind and PV branches independently and rely on batteries, as slack terminals, to absorb any possible excess energy. However, in order to protect batteries from being overcharged by realizing the constant current-constant voltage (IU) charging regime as well as to consider the wind turbine operational constraints, more flexible multivariable and non-linear strategies, equipped with a power curtailment feature, are necessary to control microgrids .The proposed strategies are novel constrained and multivariable Maximum Power Point Trackers (MPPTS) that employ renewable energy systems as flexible generators which means that their generated powers are optimally curtailed, if required, in proportion to their ratings.**

***Index Terms*— Microgrids; EMS; Power sharing; MPPT.**

I. INTRODUCTION

Microgrids are new key elements of modern power grids that improve the grids capability of hosting renewable energy and distributed storage systems. In fact, in the near future, distribution networks will consist of several interconnected microgrids that will locally generate, consume, and even store energy. Micro-grids may operate as an extension of the main grid, i.e. the grid-connected mode, or as a stand-alone network with no connection to the grid. Stand-alone sustainable microgrids have some distinct applications in avionic, automotive, or marine industries, as well as in remote rural areas. In such stand-alone microgrids, intermittent solar and wind energies coupling with battery storages contributes realistic sources to supply variable load demands [1]. However, comparing to the grid-connected microgrids, three well-known issues regarding voltage regulation power sharing and battery management, are more severe in stand-alone micro-grids leading to the necessity of more sophisticated control strategies[2][3].

Although traditionally the utility grids have always been of ac type, there are several reasons for employing dc microgrids for small-scale rural areas or commercial facilities. While ac systems benefit from the ease of transmission, transformation, distribution, and protection, they suffer from the need of synchronization of

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several generators. On the other hand, dc microgrids are more efficient due to the facts that dc generators and storages have taken higher portion of modern grids capacity and there is no need of ac-dc converters to connect them to dc microgrids.

The diversity of microgrids encompasses a wide range of configurations and goals, which will determine the energy management strategy governing each particular microgrid .The energy management strategy of a microgrid is responsible for setting the operating point of every element in the microgrid, such as the power delivered by the battery or the generators, the power used by manageable loads and the power exchanged with the grid.[4]. The works in [10] restricts the maximum attainable SOC that leads to unused capacities.

A number of phenomena affect the batteries operation during
the charging mode [8].In the field of stand-alone microgrids, when the only power sources are non-dispatchable renewable energies, the main goal is to manage the energy management system in order to keep the microgrid running, limiting the power output when necessary and sometimes using demand side management (DSM) techniques in order to avoid battery depletion. This study focuses on case 3) in which the generated power must be curtailed if it violates the batteries charging rates or if batteries are fully charged.[1] A novel energy management strategy (EMS) is proposed to address, as its control objectives, three aforementioned issues corresponding standalone dc microgrids; i.e., dc bus voltage regulation, proportional power sharing, and battery management.[6][7][9].

II. SYSTEM DESCRIPTIONS

The system consists of wind, solar, and battery branches which are connected to a dc bus through dc-coupled structures, i.e. via dc-dc converters. The microgrid supplies a variable linear dc load which is connected directly to the grid bus. From Figure 1.1, it can be seen that the presented dc microgrid is controlled by four manipulated variables, i.e. the wind turbine pitch angle and switching duty cycles of three different dc-dc converters. While increasing the wind turbine pitch angle promotes pitching to feather, the operating points of PMSG, PV, and battery bank can be changed by varying dc-dc converters duty cycles. Figure 1. Illustrates the topology of a stand-alone dc microgrid for small-scale applications.

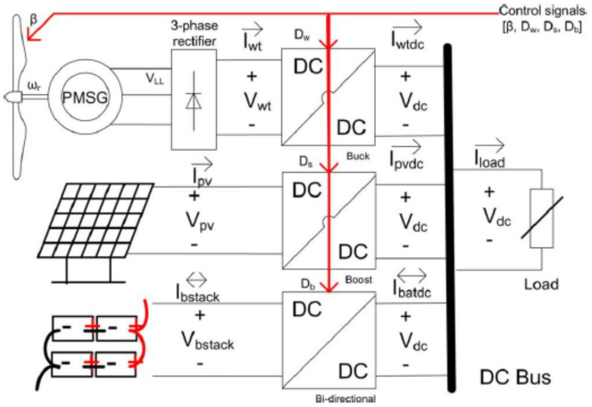


Fig. 1.1: Topology of a small-scale and standalone dc microgrid

A. Wind Branch

Wind turbines (WTs) convert the kinetic energy of wind to mechanical power. The performance of a WT can be characterized with three different curves, namely, power, torque, and thrust coeffcient curves. These curves are normally plotted in terms of tip speed ratio, which is defined as a weighted ratio of the rotational speed to wind speed, for different values of pitch angle. According to the Lanchaster-Betz theory, the upper bound of power coefficient, i.e. Cp, max, is 0.593. Modern wind turbines provide the maximum power coefficient of around 0.48 .Regarding the rotational speed, a WT operation can be classified into either constant speed or variable speed. The variable speed WT operation, which requires employing power converters, is more attractive, principally due to its ability to harvest the maximum power at variable wind speeds. In order to generate the maximum power by a WT at variable wind speed, it is necessary to employ a maximum power point tracking (MPPT) control strategy.

B. Permanent Magnet Synchronous Generators

A wind turbine can be connected to an electrical generator directly or through a gear-box. The former case, which is called direct-drive, provides some advantages in terms of high reliability and is more popular for small-scale wind turbines. To deliver power in direct-drive topology, which operates at low rotational speed, it requires employing multi-pole generators. In spite of high cost, PMSGs are the most dominant type of direct-drive generators in the market, due to several advantages such as higher efficiency.

C. Boost, Buck And Bi-Directional Dc-Dc Converters

DC-DC converters are normally implemented based on the switching-mode circuit technology containing at least one energy storage and a transistor-based power pole. However, in ideal cases, a single-pole double-throw switch can also be used for simulation purpose. While a boost-type converter, scales up its input voltage, a buck-type converter, provides lower voltage than the input voltage. Unlike the boost and buck converters which dictate the instantaneous current flow to be unidirectional, In a bi-directional converter a complementary control signal allows the current to flow in either direction.

D. Solar Branch

PVs are among the popular renewable energy components to harvest solar energy. A PV cell, as the fundamental PV element, is a P-N junction that converts solar irradiance to the electrical energy. Normally, manufacturers provide PV modules, also known as PV panels, which consist of several PV cells connected together in series. In order to construct a PV farm, at least one PV array, which is a combination of several PV modules in series and parallel arrangement, is used to provide the required power at a specific voltage level. A PV cell is a non-linear component that its operation is characterised by a set of current-voltage curves at different insolation levels and junction temperatures.

A PV module consists of several PV cells connected together in series. Although double-diode circuit provides better modelling of the loss in depletion region caused by recombination of carriers single-diode model still offers a good compromise between accuracy and simplicity. A PV array, which is a combination of several photovoltaic modules in series and parallel arrangement, can be modelled with the same circuit. Among electrical parameters, series resistor R_s is the sum of structural resistances and shunt resistor R_{SH} the leakage current. Applying Kirchhoff current law (KCL) to the junction point of these two resistors gives the characteristic equation of PV module, which is a non-linear transcendental equation.

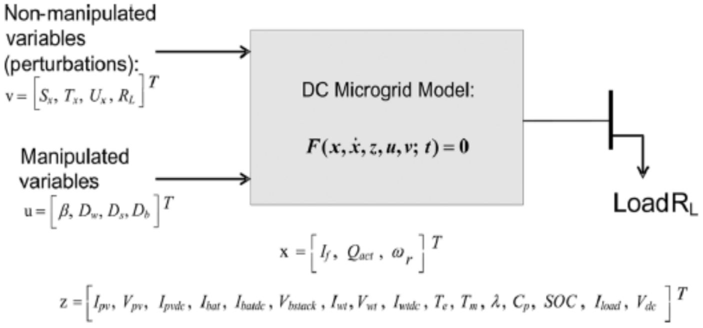


Figure1.2 : System Model

III. MPPT

Maximum power point tracking (MPPT) is a technique used commonly with wind turbines and photovoltaic (PV) solar systems to maximize power extraction under all conditions. The MPPT technique is also useful for the operation of battery. Depending upon the MPPT technique charging and discharging modes of operations of batteries are controlled. It is useful in protecting the battery from over charging, and to implement the IU charging regime of the battery that helps to increase the life span of batteries. The output power induced by the PV modules and wind turbine are influenced by number of factors which are solar radiation, temperature, wind speed etc. To maximize the power output from the system it is necessary to track the maximum power points of the individual energy sources. There are several methods to track the mpp's of the system among them P&O is the commonly used method.

IV. DESIGN AND IMPLEMENTATION OF NMPC CONTROL STRATEGY

In this work, optimal EMSs for stand-alone dc microgrids are formulated as NMPC strategies for complementarity systems. Such NMPC strategies are based on a relevant OCP in the form of MPCC for the prediction length of N sample instances. A relevant OCP includes MCPs, given by besides normal equality and inequality constraints.

$u^*(.) = \arg$ minimize $J(x(n), z(n), \gamma(n), u(n);N) :=$
$u(.)€R^n$

$k{=}nL(x(k), z(k), \gamma(k), u(k)) + M(x(n + N), z(n + N), \gamma(n + N)),$
$F(x(k), x(k + 1), z(k), \gamma(k), u(k), v(k)) = 0,$
MCP($\gamma(k)$, □($x(k), z(k)$)),
$H(x(k), z(k), \gamma(k), u(k)) \leq 0,$
$x(n) = x0, z(n) = z0, \gamma(n) = \gamma0,$
$R(x(n + N), z(n + N), \gamma(n + N)) = 0,$
$x(k)$ € X, $z(k)$ € Z, $u(k)$ € U,
$0 \leq \gamma(k) \leq 1.$

Figure 3.1 illustrates a sample of dc microgrids that is controlled with the proposed optimal energy management strategies. For the sake of simplicity, only boost side of the connected bi-directional converter is shown.

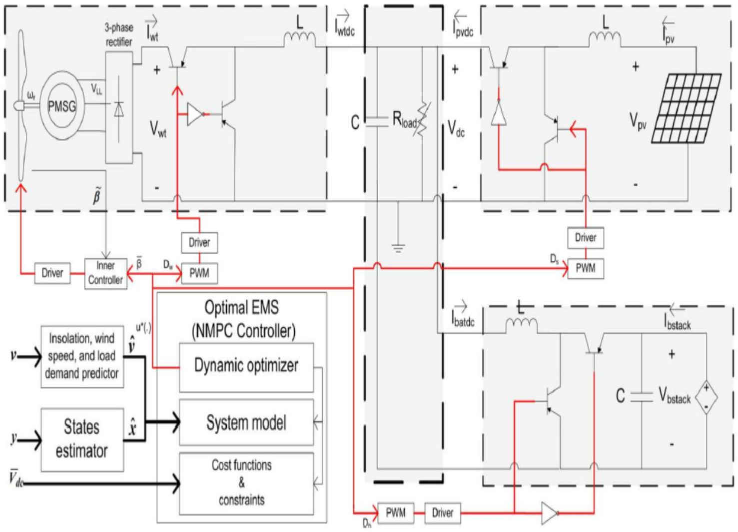


Figure: 3.1: Simplified view of the dc microgrid and the developed NMPC controller

It can be seen that the proposed EMSs iteratively get the estimated system states, ˆx, as the inputs and calculate the optimal solution, u□(.), as the outputs. It is assumed that there is an external state estimator, estimates the current system states, i.e. ˆx, from the system outputs y. The microgrid dc bus voltage level, Vdc, is set externally as a set point Vdc. The non-manipulated variables v, consisting of solar insolation, wind speed, and load demand, need to be predicted N steps ahead to be applied to the developed NMPC controller. The developed NMPC controller consists of three entities: i) the dynamic optimizer that solves the OCP successively; ii) The mathematical model, F, of the system that is used to predict the behaviour of the system with respect to the given initial value ˆx; iii) The cost function and constraints of the relevant OCP. The resulting optimal pitch angle,β, is applied as a set point to an inner closed-loop controller. Moreover, the optimal values of the switching duty cycles are applied to the pulse width modulators (PWMs) of dc-dc converters.

The proposed controller is simulated in MATLAB/SIMULINK environment. Table 1 shows the parameters of different components and their values in this study. These values are used to model the sample dc microgrid depicted in Figure. The linear load demand is also assumed to be less than or equal to 12 KW. The psuedocode of the EMS is explained in [1].

TABLE I. COMPONENT PARAMETERS IN THIS STUDY

Wind turbine		PMSG		Battery stack		PV array	
$C_1(-)$	0.517	$J(Kg.m^2)$	0.35	$C_{max}(Ah)$	48.15	$R_s(\Omega)$	0.221
$C_2(-)$	116.0	$F(N.m.s)$	0.002	$R_{bat}(\Omega)$	0.019	$R_{sh}(\Omega)$	405.4
$C_3(-)$	0.4	$P(-)$	8	$V_0(V)$	12.3024	$n_d(-)$	1.3
$C_4(-)$	5.0	$\psi(V.s)$	0.8	$P_1(-)$	0.9	$N_s(-)$	54
$C_5(-)$	21.0	$P_{rated}(KW)$	10.0	$N_{bats}(-)$	8	$I_{sc,stc}(A)$	8.21
$C_6(-)$	0.007	$L_s(H)$	0.0083	$N_{batp}(-)$	3	$V_{oc,stc}(V)$	32.9
$\lambda_{opt}(-)$	8.1			$T_s(sec)$	0.726	$k_I(A/K)$	0.003
$P_{wt,nom}(KW)$	10.0			$V_{bstack,nom}(V)$	96.0	$k_V(V/K)$	-0.12
Rad (m)	4.01			$P_{bat,nom}(KW)$	1.296	$N_{pvs}(-)$	1
$U_{x,base}(m/s)$	12.0			$C_{10}(Ah)$	45.0	$N_{pvp}(-)$	10
$C_{p,max}(-)$	0.48			$V_{gas}(V)$	13.0	$P_{pv,nom}(KW)$	2.001

The psuedocode of the proposed EMS is explained in [1]

IV. SIMULATION RESULTS

The simulink model of the system is shown in figure 3.2.

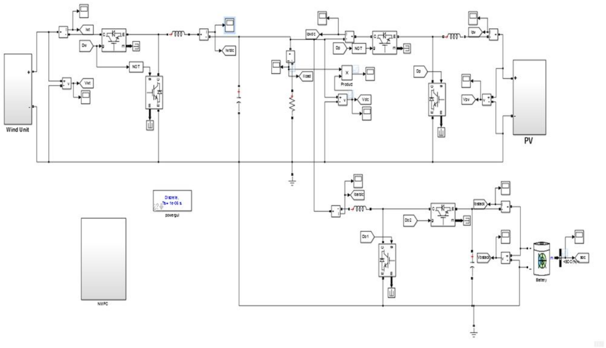
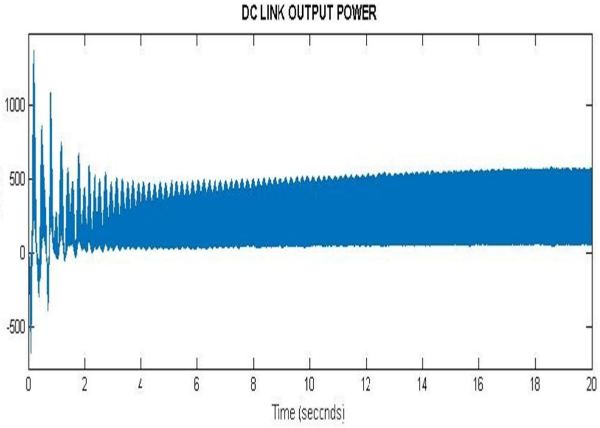


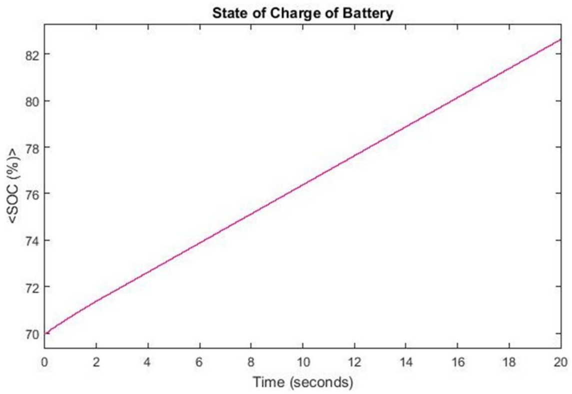
Figure:3.2: Simulink model of the system

Figure (a) and (b) shows the output power and the SOC of the battery obtained while applying MPPT control strategy and the figure (c) and (d) shows the output power and SOC of the battery obtained when NMPC control strategy is applied.

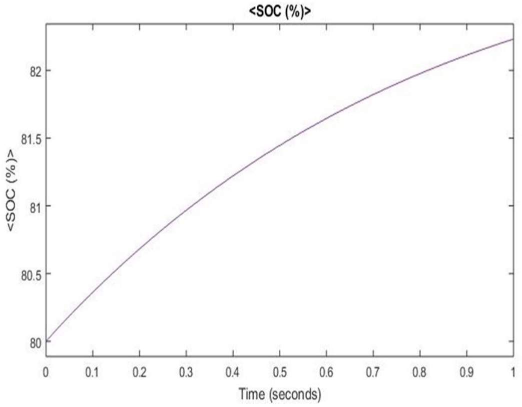
The system is analysed when the battery is working under charging condition .It is seen that there is a linear increase in the SOC of the battery when both MPPT and NMPC control algorithms are applied. However NMPC control algorithm is seen to yield better output power of about 8KW compared to the output power obtained applying the MPPT control algorithm. It is seen that the fluctuations in output power is also minimized.



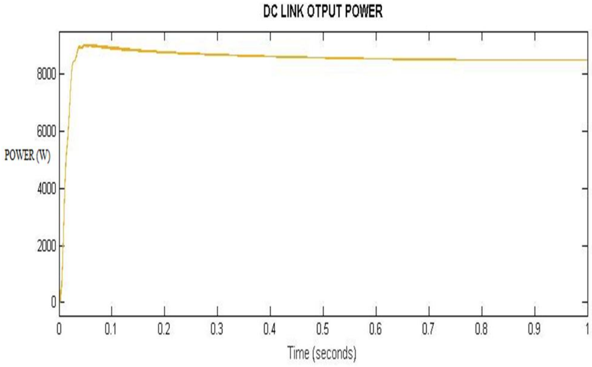
(a)



(b)



(c)



(d)

V. CONCLUSION

This work comprises a study on modelling, simulation and control of stand-alone dc microgrids for the purpose of developing dynamic energy management strategies. It is shown that, employing new available nonlinear optimization techniques and tools, the computational time to solve the resulting NMPC strategy is in permissible range. Unlike dump load-based strategies that only protect the battery from overcharging, the proposed strategy implements the IU charging regime that helps to increase the batteries life span.

Moreover, removing dump loads, the overall installation cost is reduced. It is shown that the energy management strategies are non-linear multivariable optimal control problems. This work involves formulating optimal control problems and developing non-linear model predictive control strategies to optimally manage energy flows across stand-alone dc microgrids. The simulation results show its ability to achieve all control objectives.

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