An Effective Finite Control Set-Model Predictive Control Method for Grid Integrated Solar PV

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ABSTRACT The grid integration of a photovoltaic solar system operating with maximum power point tracking is being presented in this paper. The system uses a dc-dc converter for power tracking while employing finite control set model predictive control (FCS-MPC) to govern the dc-ac inverter. An effective control scheme that employs only FCS-MPC in the entirety of its control layer is proposed, where three control objectives; the regulation of the dc-link voltage, the injection of active power, and the injection of reactive power to the main grid have been achieved within a single cost function. The controller avoids translating dc-link voltage deviations to the active power reference and controls all variables directly in the cost function. The controller’s feasibility has been evaluated through experiments where experimental testing using OPAL-RT has been carried out to prove the concept. The results show that all three control objectives can be achieved efficiently using the proposed method, with minimal error in the controlled variables. Furthermore, the controller shows high robustness against parameter mismatch and grid inductance variations.

INDEX TERMS DC-link voltage control, discretized control, grid connected energy source, two-level inverter control, maximum power point tracking control, weighting factor tuning.

I. INTRODUCTION

The integration of intermittent solar energy to the utility grid poses many challenges due to its effect on the quality of the power injected into the grid as well as the stability of the grid. In the grid connected mode, the solar PV must operate in maximum power point tracking (MPPT) mode to be efficient in extracting the optimal available power. With variations in atmospheric temperature and irradiance levels, resulting naturally from the sun’s position in the sky or from environmental shading events, the amount of available power varies. The operating voltage of the solar PV must therefore be shifted to extract optimal power. MPPT control can be implemented by including a dc-dc boost converter as an intermediate stage between the inverter and the PV solar panel. Alternatively it can also be implemented directly with the control of the smart inverter.

During the MPPT operation mode, one main element susceptible to instability is the voltage across the dc-link capacitor. As the operating voltage is changed, the dc-link capacitor’s voltage is prone to fluctuation. Furthermore, at the event of load transients, the PV array holds the possibility of collapsing the dc-link voltage. These events result in an ac voltage drop and can lead to instability and poor power quality in the grid system. Furthermore, the voltage at the dc-link capacitor is typically the point of connection for the energy storage system. In order to evade the rise and drop in the dc-link voltage it is crucial that the dc-link voltage is controlled at a constant level. This helps not only in maintaining stable power injection to the
grid but also avoids the overcharge and over discharge of storage systems.

While the solar PV panel directly produces only active power, the inclusion of smart inverters enables the injection of reactive power into the utility grid. Reactive power compensation maintains grid stability during voltage sags and swells and over voltage scenarios. Active and reactive power can be simultaneously regulated by varying the amplitude and phase of the output voltage of the smart inverter. The dc-ac inverter enables the control of active and reactive power injection into the grid and can be implemented in single phase or two-level inverters. In order to sustain the stability of the utility grid, it is imperative that the quality of the injected power is within the IEEE 1547 standard which delineates the requirements for the interconnection of distributed generation resources into the power grid [1].

MPPT, dc-link voltage control and power injection are accomplished in numerous ways in the existing literature for the adaptation of solar PV with the utility grid. Some techniques include using solely proportional-integral (PI) controllers, solely model predictive controllers or a combination of both, to smoothly integrate intermittent energy to the existing grid.

Some early research efforts include the use of multiple interlinking converters with cascaded PI controllers to achieve accurate power sharing as well as maintaining the dc-link voltage. For instance, in [2] the dc-dc bidirectional boost converter of the battery controller regulates the dc-link voltage, while the dc-ac converter regulates power exchange between the PV source and microgrid. In [3] multiple PI control loops are implemented to achieve MPPT along with voltage, frequency, active and reactive power injection between the solar PV, battery storage system and the utility grid. Two simultaneous PI control loops have been used in [4] for reactive power and dc-link voltage control by adjusting the inverter’s reference voltage amplitude and phase angle. There exist other methods that exclude the use of PI controllers. Finite control set model predictive control (FCS-MPC) comprises the use of a discrete model of power converters and can be used to integrate solar PV power to the microgrid seamlessly. It can operate by maintaining optimum power quality when assisting the utility grid or independently sustaining loads when the utility grid is not present. The implementation of FCS-MPC in distributed energy sources can be found in numerous sources [5]–[9]. The FCS-MPC strategy itself is highly sensitive to the dc-link voltage level due to its presence in the mathematical model of the predictive algorithm, specifically in computing the candidate voltage vectors suitable to the selected inverter topology, further advancing the need to regulate the dc-link voltage at a stable level.

In [10], a dynamic reference algorithm is proposed where the active power reference is dependent on the predictive horizon of the dc-link voltage. However, with this method there is a nonzero steady state error when the inverter must supply reactive power or in the case of a parameter mismatch. In order to overcome the above issue with the steady state error, [11] offers an alternative predictive control which, instead of having a fixed input power reference, calculates it based on the output active power, the reactive power and energy stored in the dc-link capacitor. The calculation of a power differential and the outer power result in the generation of the active power reference. This method, while excluding the estimation of linear controller design parameters and showing no steady state error, does nonetheless result in a slow dynamic response compared with the PI control method. Authors in [12], [13] avoid the use of a boost converter and achieve MPPT and power sharing using exclusively FCS-MPC. Here the output of the MPPT is used as a current reference in the current controlled cost function of the model predictive controller.

Control of the dc-link capacitor voltage can be incorporated in the optimization equation directly. Articles found in [14], [15] and [16], [17] present the concept of including capacitor voltage imbalance in the cost function of a multi-objective optimization in single phase and multi-level inverters respectively. The design includes a weighting factor that provides a trade-off to shift the control objective between the output current and the dc link capacitor’s voltage imbalance. In [14] a single phase H-bridge neutral-point-clamped (NPC) inverter is used along with optimal switching state model predictive control. The methodology is able to achieve both control aims with zero error. A three-level-NPC multilevel inverter topology is similarly proposed in [16] and makes use of FCS-MPC. Although these methods simplify control by eliminating linear controllers and provide a good dynamic and steady state performance, they result in an increase in the amount of mathematical calculations per control cycle and give rise to additional design complexity due to the presence of a weighting factor.

A series of methods make use of both PI and MPC methods to achieve control of MPPT, dc-link voltage and power control. The closed loop control of the dc-link voltage is achieved by using a proportional-integral (PI) linear controller to translate the voltage offset to an active power reference value for the MPC based smart inverter. In [18] and [19] the linear controller is used to control the active power reference. Authors in [20] utilize just one inverter and enable both MPPT and power control by passing MPPT information to a voltage reference, avoiding the use of dc-dc converters and therefore power losses. The voltage error is minimized using a PI controller and the resulting output is used to create the power reference to the MPC controller. Similarly, [21] introduces multiple PI controllers to control the dc-link voltage while employing MPC on the current injected into the grid. These methods, despite resulting in zero steady state error due to the presence of linear controllers, still hold the difficulty of tuning PI control parameters.

Most other control techniques that use FCS-MPC for the integration of PV solar power to the grid include either; PI control in the outer loop to control power reference to the model predictive controller, or a dynamic power reference controller in the outer loop to stabilize the dc-link voltage.
The technique provided in this paper implements a similar theory of capacitor voltage balance but for a two-level inverter and excludes dc-link voltage control in the outer control loop, simplifying the control design process. For the proposed methodology, in grid-connected mode, the dc-ac interlinking converter is used to not only sustain a stable dc-link voltage but to also perpetuate accurate power injection from the distributed energy source to the main grid. Moreover, the dc-dc boost converter is used to track the maximum available power from the solar PV array.

The main contribution in this control methodology is that this FCS-MPC technique uses the model of components from the input side of the inverter to achieve dc-link voltage control. Existing studies [10]–[17] focus on using dc measurements while this study considers AC measurements also for the control of the dc-link voltage. AC side current along with the switching state is used for the prediction of the dc voltage. This improves the dynamic performance of the controller while enabling dc voltage control within a single cost function. As a result, all control objectives are included in one cost function. As a result, the developed control technique is purely based on MPC without any other controllers. This approach avoids the use of multiple cascaded PI controllers and implements the control of active power, reactive power and dc-link voltage in a single MPC equation, offering less complex design efforts and a reduction in the number of parameters to be tuned. The classical multi-nested loop control schemes require substantial tuning effort particularly for decoupled active and reactive power control of two-stage grid interactive PV inverters. The proposed approach provides a straightforward approach for decoupled active and reactive power control of grid-interactive PV inverter by a single loop optimization without substantial tuning effort. Furthermore, in comparison to existing MPC techniques for dc-link control in a single cost function, this technique avoids the cumbersome calculation stage of transferring voltage deviations to reference power values and instead, directly controls all variables in the cost function.

The structure of this paper is such that; in Section II the modelling of the test system and existing controllers are presented, in Section III the proposed controller with its modifications is presented, in Section IV experimental results of the developed controller are presented and discussed and finally Section V concludes the paper.

II. MODEL OF THE SYSTEM

The comprehensive system layout for the integration of solar PV to the grid is as seen in Fig. 1. The energy production...
side consists of an array of solar panels, followed by a dc-dc boost converter, a dc-ac voltage source inverter (VSI) and an LC filter.

A SOLAR PV-ARRAY MODELLING
A 1.1kW solar array is designed as can be found in numerous literature by modelling a single cell diode and consequently creating a block of solar arrays by connecting the cells in series to form a string of modules. Subsequently the connection of multiple strings in parallel form an array. Specifications for the solar PV system are detailed in Section IV.

B. DC-DC CONVERTER MODELLING WITH MPPT
The dc-dc converter is a boost converter and steps up the fluctuating voltage from the solar panel to a stable voltage at the dc-link, $v_{dc}$. The dc side capacitor’s value is calculated based on the allowed voltage ripple on the dc side ($V_{ripple}$), the rated dc-current under full supply capacity ($I_{rated}$), the average switching frequency ($f_{sw}$) and a 1.5% safety factor as seen in (1). $I_{rated}$ is calculated based on the rated power of the PV array ($P_{rated}$) and $v_{dc}$, while $V_{ripple}$ is allowed to be 1% of the nominal dc-link voltage. For MPPT, the perturb and observe (P&O) approach has been selected in this article, where the control algorithm uses measured voltage and current from the solar PV system to observe changes to the deviation of power and voltage at each control time step. The flowchart of the MPPT control technique is shown in Fig.2 [22].

$$C_2 = \frac{(1.5)I_{rated}}{V_{ripple}f_{sw}}$$ (1)

C. INVERTER AND FILTER MODELLING
Following the boost converter stage, the dc power needs to be inverted to ac power in order to be integrated with the utility grid. A VSI, whose topology is seen in the red block in Fig. 1, is employed for the production of three phase power. Its main feature is that it converts dc voltage to nominal ac-voltage with a nominal frequency. More information on the VSI can be found in [23]. Due to limitations of the available laboratory grid emulator, an AC voltage of 70Vrms is maintained. Accordingly, the minimum input dc link voltage should be $V_{dc} = (2V_{rms})/M = 172V$, to maintain 70Vrms at the output (with $M = 2/\sqrt{3}$), where, $M$ is the modulation index and $V_{LN}$ is the maximum value of the voltage waveform [24].

Thus, the dc voltage across capacitor $C_2$ is regulated at 200V. Furthermore, during the modelling of the inverter, the three phase voltages are assumed to be balanced and without any zero sequence components. The semiconductor switches in the two-level three phase inverter allow a combination of eight different switching states as seen in Table 1, resulting in 7 different voltage vectors $V_{inv}$, at the output of the inverter, where each z represents a specific switching sequence and $V_{dc}$ is the dc-link voltage. The derivation of these voltage vectors, and consequently current vectors, are explained in more detail in Section III.

Due to the switching operation of the two-level VSI, the output current and voltage are not exclusively sinusoidal and require a filtering stage before the power can be integrated into the utility grid. An LC filter is sufficient to attenuate the harmonic content of the power to meet the requirements of specifications set by the IEEE 1547 standards for the power quality of distributed energy sources [1]. The selection of LC filter parameters, $L_f$ and $C_f$ are based on the rated power of the inverter and other factors as can be found in [25] for the design of an LC filter for a three phase inverter. The remainder of the plant system consists of a grid side inductance and a balanced three phase utility grid.

D. MODELLING OF TRADITIONAL FCS-MPC
The output power regulation of the above inverter has been realized by using a FCS-MPC scheme. FCS-MPC essentially involves a discretized mathematical model of the inverter, a current prediction stage and the optimization of a cost function. The traditionally used direct power control scheme, which is prevalent in the literature for FCS-MPC will be derived in this section and the modified control scheme will be introduced in Section III. FCS-MPC is used to operate the inverter as a current controlled VSI to inject active and reactive power into the utility grid. A constant voltage is fed into the inverter and at the output side, the current is predicted. This predicted current is used to calculate and
TABLE 1. Switching states and corresponding output V-I vectors for two-Level VSI.

| \( z \) | \( S_{a,z} \) | \( S_{b,z} \) | \( S_{c,z} \) | Voltage Vector \((V_{in,z})\) | Current Vector \((I_{Lf,z})\) |
|------|------|------|------|----------------|----------------|
| 0    | 0    | 0    | 0    | 0               | 0              |
| 1    | 1    | 0    | 0    | \( \frac{4}{3}v_{dc} \) | \( i_s \)        |
| 2    | 1    | 1    | 0    | \( \frac{4}{3}v_{dc} + j\frac{\sqrt{3}}{3}v_{dc} \) | \( \frac{1}{2}i_s + j\frac{\sqrt{3}}{2}i_s \) |
| 3    | 0    | 1    | 0    | \( -\frac{1}{3}v_{dc} + j\frac{\sqrt{3}}{2}v_{dc} \) | \( -\frac{1}{2}i_s + j\frac{\sqrt{3}}{4}i_s \) |
| 4    | 0    | 1    | 1    | \( -\frac{1}{2}v_{dc} \) | \( -i_s \)        |
| 5    | 0    | 0    | 1    | \( \frac{1}{4}v_{dc} - j\frac{\sqrt{3}}{2}v_{dc} \) | \( -\frac{1}{2}i_s - j\frac{\sqrt{3}}{4}i_s \) |
| 6    | 1    | 0    | 1    | \( \frac{1}{2}v_{dc} - j\frac{\sqrt{3}}{4}v_{dc} \) | \( \frac{1}{2}i_s - j\frac{\sqrt{3}}{2}i_s \) |
| 7    | 1    | 1    | 1    | \( 0 \)           | \( 0 \)            |

enable the injection of active and reactive power into the distribution grid. As seen in Fig. 1, the design procedure for traditional FCS-MPC involves; the measurement of three-phase voltages and currents at the point of common coupling (PCC), conversion of these values from abc to \( \alpha\beta \) frame using Clarke transformation, prediction of the future current and consequently the active and reactive power, minimization of the cost function to track active and reactive power references and finally the selection of switching states for the inverter’s switches. The design procedure for traditional direct power control FCS-MPC is as below.

1) MODELLING DYNAMIC EQUATION OF \( L_f \)
In order to predict the current at the PCC, the mathematical model of the dynamic current across filter inductor \( L_f \) must be derived. From the single phase circuit diagram in Fig. 3, the differential equation for the current across the inductor can be derived as in (2), where \( V_{in} \) is the resulting voltage vector from the inverter’s switching states and can be one of eight possible vectors.

\[
V_{in} = V_{Lf} + V_c = L_f \frac{di_{Lf}}{dt} + V_c \tag{2}
\]

2) PREDICTING CURRENT AT THE PCC
Subsequently, following Euler’s discretization, the predicted current across the inductor can be obtained as in (3), where \((k)\) represents the present time step and \((k+1)\) refers to the future time step.

\[
i_{Lf}(k+1) = \frac{T_s}{L_f}(V_{in,z}(k) - V_c(k)) + i_{Lf}(k) \tag{3}
\]

3) PREDICTING ACTIVE AND REACTIVE POWER INJECTION
The predicted current and the measured voltage at the PCC are utilized as in (4) and (5) to predict the active and reactive power for the future time step.

\[
P_{k+1} = \frac{3}{2}(V_{a}(k)i_{a}(k+1) + V_{\beta}(k)i_{\beta}(k+1)) \tag{4}
\]

\[
Q_{k+1} = \frac{3}{2}(V_{\beta}(k)i_{a}(k+1) - V_{a}(k)i_{\beta}(k+1)) \tag{5}
\]

4) DEVELOPING COST FUNCTION
Finally the cost function \( g \) is minimized to select the optimal switching sequence for the subsequent switching instance, where \( P_{ref} \) is the multiplication of \( V_{dc} \) and \( I_{dc} \).

\[
g = |P_{ref} - P_{(k+1)}| + |Q_{ref} - Q_{(k+1)}| \tag{6}
\]

III. DEVELOPED CONTROL TECHNIQUE
A. MODELLING OF DEVELOPED FCS-MPC
For the proposed control methodology, the inverter controller is employed to both preserve a stable dc-link voltage and sustain accurate power sharing between the distributed energy source and the grid, while the dc-dc boost converter is used to track the maximum available power from the solar PV array. The main contribution arises from adding the control of dc-link voltage in the FCS-MPC as an additional control variable in the cost function.

The design procedure for the developed FCS-MPC involves the steps outlined below. First, the dynamic equation of the model of \( C_2 \) is used to predict the future dc-link voltage. The predicted dc-link voltage is then included for error minimization in the cost function along with active and reactive power as seen in the control schematic of Fig.1. The proposed FCS-MPC technique requires the measurement of the inverter dc side current \( i_{dc} \), which includes the effect of the switching state of \( S_{dc} \), for the prediction of the \( v_{dc} \).

1) MODELLING DYNAMIC EQUATION OF \( C_2 \)
In order to include the dc-link voltage in the cost function, the predicted value should first be calculated based on the...
measured data. The mathematical model of the dynamic voltage across the dc-link capacitor (7) is utilized, in juxtaposition to the current across the filter inductor, which was used previously to predict active and reactive powers. The scalar current into the inverter $i_k$ can be related to the vector currents at the output of the inverter, that is the current across the filter inductor $I_{L_f}$, using (8). Here, $S_z$ is one of eight switching vectors resulting from the combination of the switching states of each leg $S_{a,z}, S_{b,z}$ and $S_{c,z}$. The comparison of these vectors can be seen in Table 1 and are derived as seen in Fig. 4, for a selected switching sequence.

2) PREDICTING VOLTAGE AT THE PCC
Similar to before, following Euler’s discretization, the predicted voltage across the capacitor can be obtained as in (9), by replacing $i_k$ in (7) with (8), and rearranging the variables. Due to the control frequency being much higher than the system frequency the predicted output current is used in replacement of estimating the actual output current.

$$i_{k+1} = S_z i_k + \frac{T_z}{C_z} - \frac{I_{L_f(k+1)}}{S_z}$$

3) DEVELOPING COST FUNCTION
The new cost function $g'$ is developed as in (10) and now encompasses multiple control variables. A weighting factor $\lambda$ is therefore incorporated to allow tuning of the FCS-MPC controller to adjust the importance on power injection or voltage regulation during the operation of the inverter.

$$g' = |v_{ref} - v_{dc(k+1)}| + \lambda [|P_{ref} - P_{k+1}| + |Q_{ref} - Q_{k+1}|]$$

**B. DERIVATION OF $V_{in}$ AND $I_{L_f}$ BASED ON EACH SWITCHING STATE**
As derived in [26], the output voltage vectors can be defined based on the switching signals. For demonstrating purposes let us consider the switching state of $Z_1 = (1, 0, 0)$, where the upper switch of phase leg $a$, and lower switches on phase legs $b$ and $c$ are conducting. The equivalent load configuration is as seen in Fig. 4. Based on voltage division, the voltage across each phase ($v_a, v_b, v_c$) can be realized. Similarly, the phase currents ($i_a, i_b, i_c$) across each leg can also be obtained based on Kirchhoff’s current law. The output voltage and current vectors can then be constructed based on equations (11) and (12), where $e^{\frac{j\pi}{2}}$ represents a phase shift of 120° and $e^{\frac{j\pi}{3}}$ a phase shift of 240°, to create a balanced three phase vector. Similarly voltage and current vectors can be derived for all the switching states as seen in Table 1.

$$V_{in1} = \frac{2}{3} (v_a + v_b e^{\frac{j\pi}{2}} + v_c e^{\frac{j\pi}{3}}) = \frac{2}{3} V_{dc}$$

$$I_{L_f1} = \frac{1}{3} (i_a + i_b e^{\frac{j\pi}{2}} + i_c e^{\frac{j\pi}{3}}) = i_s$$

**FIGURE 4.** Circuit configuration, voltage vectors and current vectors for switching state $z = 1$.

**IV. RESULTS AND DISCUSSION**
The performance of the proposed controller has been tested in MATLAB/Simulink for its performance and consequently validated experimentally using the test bed shown in Fig. 5. The controllers of MPPT and MPC have been implemented on the OP5600 target platform. The EA PSI 9750-12 dc power supply has been used to emulate a solar PV array and supply variable voltage by changing irradiances.

For the purpose of this paper the PV system, whose specifications are as seen in Table 2, has been selected. $V_{oc}$ is the open circuit voltage, $I_{sc}$ is the short circuit current, $V_{mp}$ is the voltage at maximum power, $I_{mp}$ the current at maximum power and $P_{mp}$ is the maximum power at 100% irradiance. The inverter consists of SiC power switches and the device is rated to handle a maximum of 600V at the input, 200kHz maximum switching frequency and up to 6.1kW of power at 25°C. Selected component values and parameters for the two converters and LC-filter are listed in Table 3.

The control algorithms designed in Simulink are built and compiled using RT-Lab software and subsequently loaded and run in OPAL-RT. The experimental data have been logged onto the Yokogawa Scope Recorder oscilloscope for displaying and analyzing useful measurements. The measurements are discretized using forward Euler discretization and operated at a sampling time of 10μs. The procedure required to integrate the offline control model from Simulink software to RT-Lab software and consequently perform experimental testing is detailed as seen in Fig. 6.

**A. EFFECTIVENESS OF FCS-MPC CONTROLLER**
In order to verify the implementation of the proposed FCS-MPC, five case studies have been carried out. The first case shows the effectiveness of the P&O MPPT controller. The second case shows the ability of the controller to handle transient operations. The third and fourth cases demonstrate the ability of the controller to achieve active power and reactive power tracking while regulating the dc-link voltage. The fifth and final case shows the effect that the weighting factor has on the control of the subjected variables. It should be noted that in all case studies the temperature is fixed and constant at 25°C.
1) CASE 1: PERFORMANCE OF MPPT CONTROLLER

In case 1 the control of the boost converter is tested for its ability to track the maximum power point with changing irradiances. The boost converter ensures that the PV system is operating at the voltage that produces the maximum power for a given irradiance and temperature. In this case, the irradiance is increased from 400W/m$^2$ to 700W/m$^2$ over a few seconds.

The resulting power generated by the solar PV, $P_{\text{ref}}$, is plotted along with $P_{\text{ideal}}$, the ideal power that the PV array would produce at that irradiance. The resulting power is labelled as the reference power as it will be the reference to the FCS-MPC in the next control stage. As seen on Fig. 7, the first plot line shows the efficiency of the MPPT controller. The calculation for the system efficiency ($\eta$) and the ideal power ($P_{\text{ideal}}$) are as seen in (13) and (14) where, $P_{\text{max}}$ is 1.2kW and $P_{\text{pv}} = V_{\text{pv}} I_{\text{pv}}$.

$$\eta = 1 - \frac{|P_{\text{ideal}} - P_{\text{pv}}|}{P_{\text{ideal}}}$$

$$P_{\text{ideal}} = \frac{I_{\text{ref}} P_{\text{max}}}{1000}$$

2) CASE 2: STEADY STATE AND TRANSIENT OPERATION OF FCS-MPC

The second case study helps observe the steady state and transient performance of the FCS-MPC. In this case the irradiance sharply dips from 700W/m$^2$ to 300W/m$^2$ over a few seconds. The reactive power reference is kept constant at 500VAr. The dip in the irradiance is simulated to mimic the movement of clouds, creating partial shading conditions and allowing the transient analysis of the system.

As can be seen in Fig. 8, there is little effect on the active and reactive power tracking. The voltage tracking is affected more severely as the voltage increases approximately 25% above the regulated level. Fig. 8 shows the effect of the change in irradiance on the three phase output current and voltage of
3) CASE 3: ACTIVE POWER TRACKING CAPABILITY
The ability of the proposed algorithm to handle both dc-link voltage regulation and power control in one cost function has been validated in this case. For observing active power tracking, once again an irradiance profile similar to that of case 1 is used, resulting in the power reference $P_{ref}$ increasing gradually. In this case, the irradiance rises from 400W/m$^2$ to 700W/m$^2$ over a few seconds. The reactive power reference $Q_{ref}$ is constant at 500V AR. As can be seen in Fig. 10, active power is being injected accordingly while the dc-link voltage regulation and reactive power tracking are not affected.

4) CASE 4: REACTIVE POWER TRACKING CAPABILITY
The next test is done in order to observe the dynamic tracking of reactive power. The reactive power is generally dictated by static VAR compensators and are typically used to compensate for sags and swells in the output voltage. In this case, $Q_{ref}$ is gradually increased from 100VAR to 500VAR over a time span of a few seconds. The irradiance is kept constant at 500W/m$^2$. As can be seen in Fig. 11, reactive power is being injected accordingly while the dc-link voltage regulation and active power tracking are not affected.

5) CASE 5: EFFECT OF THE WEIGHTING FACTOR ($\lambda$)
The weighting factor has an imperative effect on all the control variables; the active power, reactive power and the dc-link voltage. In order to simplify the tuning of $\lambda$, the powers and dc link voltage have been normalized to have a similar effect on all control variables. An increase in $\lambda$ improves power tracking while worsening voltage regulation and vice versa. In this case study $Q_{ref}$ is kept constant at 500VAR and the irradiance is kept constant at 500W/m$^2$. The weighting factor is initially at 1.2 and gradually reduces to 0.4.

Fig. 12 shows the experimental implementation to test the effect of $\lambda$. As observed, at high $\lambda$, the powers are tracked at their desired values, but lessen their controllability.
as $\lambda$ is reduced. Conversely, the dc-link voltage is initially not controlled as it fluctuates about 240V, resulting in fluctuations to $P_{\text{ref}}$ as well, as seen in Fig. 12. When $\lambda$ is gradually decreased and low enough to activate voltage regulation, the dc-link voltage is controlled at 200V. The optimal $\lambda$ is selected in the mid-range to be $\lambda = 0.85$, where all control objectives are satisfied.

**B. EFFECT OF MODEL PARAMETER VARIATION**

The values of the filter inductor ($L_f$) and the dc-link capacitor ($C_2$) are both utilized in the prediction equations, and assumed to be non-varying parameters. However, in reality, with prolonged operation, the actual capacitance and inductance vary from their nominal values due to altering external conditions such as temperature. Due to this reason, the robustness of the controller to variations in these components have been studied here. In this experiment, the value of the components in the plant are kept constant while the value in the control algorithm have been changed in percentage step sizes of the rated amount. All other variables are kept constant with $\lambda = 0.85$, $I_{\text{irr}} = 500\text{W/m}^2$, $Q_{\text{ref}} = 500\text{VAR}$ and $V_{\text{ref}} = 200\text{V}$.

Fig. 13(a) shows the percentage errors of the controlled variables for filter inductance variation from 20% lower than its rated value to 20% higher. Fig. 13(b) shows the same for variation in the dc-link capacitance. The percentage error for the reactive power is highest due to its low reference, and therefore low importance, in the cost function. Nevertheless, despite a ± 20% variation in the values of $L_f$ and $C_2$, the tracking errors remain under 2%. This shows that the proposed control is robust against parameters mismatch.

**C. EFFECT OF VARIATION OF GRID IMPEDANCE**

Typically, the grid side impedance changes in real-time due to loads and other distributed energy sources being switched in and out of the grid system. The controller’s ability to operate with low error during grid inductance variation is therefore important and has been examined in this case. This has been done by observing the percentage errors for power and voltage while varying the grid inductance from 0mH to 20mH. As seen in Fig. 14, the reactive power error is higher, however all other errors are maintained under 1.2%.

The variation of $L_g$ does not cause a high error in the control process due to the fact that voltage and current measurements are taken close to the inverter and before the grid inductance. Therefore, even if $L_g$ changes and creates a higher or lower current to flow in the line, the value of the measured current $i_{L_f(k)}$ also changes and the controller has to now select an inverter voltage vector $V_{\text{in}}$ in order to minimize the cost function. Fig. 15 shows how the predicted current changes due to the $V_{\text{in}}$ changing for a grid inductance of 1mH and 20mH. The controller is able to iterate this process and remain robust to grid inductance variations until and unless the grid inductance is so high to a point that it requires more power than the solar array can provide. However this situation is resolved since a grid connected system is used and an increase in demands higher than the solar production will be compensated by the grid.
TABLE 4. Feature comparison for existing and proposed control schemes.

| Controller Feature                                | Converter Controllers       | PI based [2]–[4] | PI and MPC based [18]–[21] | MPC Reference based [10]–[13] | MPC Cost Function [14]–[17] | Proposed Control |
|--------------------------------------------------|-----------------------------|------------------|----------------------------|--------------------------------|-------------------------------|------------------|
| Number of parameters requiring tuning per distributed generator | 2 to 6                       | 1 to 3           | None to 2                  | None to 1                      | 1                             |                  |
| Computational burden                              | Low                          | High             | High                       | High                           | Moderate                      |                  |
| Steady state error                                 | Low                          | Moderate         | Relatively high            | Relatively high                | Moderate                      |                  |
| Dynamic control time                               | Moderate                     | Moderate         | Relatively high            | Short                          | Short                         |                  |
| Nature of switching frequency                     | Fixed and specific           | Fixed or varying depending on control mandate | Continuously varying, broad range | Continuously varying, broad range | Continuously varying, broad range |                  |
| Complexity of design model                         | Complex if multiple PI controllers used | Complex | Complex | Simple | Simple |                  |

The previously mentioned existing control strategies have been categorized and compared in Table 4, where ‘PI based’ includes solely PI centered cascaded controllers, ‘PI and MPC based’ comprises those methods that use both PI control followed by MPC, ‘MPC reference based’ involves those that convert control variable deviations to reference values in the cost function, ‘MPC cost function based’ comprises control schemes that involve the direct control of variables in the cost function with MPC only and finally the proposed control scheme.
V. CONCLUSION

In this paper, FCS-MPC of a grid connected PV inverter was proposed and tested experimentally. A simple control scheme for the integration of a solar PV system to the grid was introduced, evaluated, and validated in this paper. The system includes a dc-dc converter with MPPT and dc-ac inverter with FCS-MPC. The FCS-MPC controller was designed to both regulate the dc-link voltage and the injection of active and reactive power in a single cost function. This was achieved by discretizing the model of the dc-link capacitor and subsequently using measured dc current to predict the dc-link voltage in the cost function. The experimental operation results show accurate power injection while regulating the dc-link voltage. The MPPT controller tracked the maximum power point while the FCS-MPC achieved accurate power injection to the grid while regulating the dc-link voltage under varying irradiance values. The proposed controller was also tested to prove the robustness against variations to system parameters and the results showed an error of less than 1.4%. Finally, the system was also shown to be robust against changes to the grid inductance with errors less than 1.2% in all three controlled variables. The proposed control mechanism can be deployed in the interconnection of any distributed energy source that requires the control of a dc-link stage and can be utilized with the FCS-MPC algorithm. It has a low steady state error, good transient performance, and is much simpler to design. Furthermore, it is devoid of a PWM signal modulation stage and allows the easy addition of several control variables. In conclusion, a simple control scheme for the integration of a solar PV system to the grid has been has been presented, evaluated and validated.

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