# An Accurate MPPT Scheme for Photovoltaic Modular-Based Conversion Units: A Robust Sensorless Predictive Approach

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***Abstract*—This research presents a Maximum Power Point Tracking (MPPT) algorithm for a solar photovoltaic (PV) power station which is constructed based on modified circuit topology of the Modular Multilevel Converter (MMC). The proposed MPPT is featured with Optimized Finite-Control-Set Model Predictive Control (FCS-MPC) to provide continuous extraction of maximum solar energy. The estimation-based approach allows for elimination of the current sensors in PV panels unlike the well-proven MPPT methods, e.g., perturb and observe (P&O) and ripple-correlation control (RCC), where costly sensing devices are widely deployed. With developed control strategy, fast tracking response for the PV plant along with acceptable control bandwidth under solar irradiation transients and PV panels mismatch are achieved. The introduced circuit of power conversion has led to decreased number of solar cells and a 50% reduction of the energy storage sizing compared to the basic MMC configuration. The effectiveness of the discussed MPPT solution over the solar irradiance variations is compared with the both P&O and RCC methods. The behavior of the studied PV system is also evaluated under different operational scenarios through simulations to confirm the designed concept.**

***Keywords—Multilevel Power Converter; Maximum Power Point Trackers, Photovoltaic generation, Model Predictive Control; Sensorless operation; Optimization problem***

## I. INTRODUCTION

More and more demand in installed renewable generation resources, in particular solar photovoltaic (PV) plants are foreseen reach up to 3000 GW, approximately 12% of the global electricity production. As a matter of fact, the global cumulative PV capacity has raised more than four times over the past five years [1, 2]. Between 2010 and 2015, global average costs for utility-scale solar PV declined by 60%, and therefore this trend is predicted to reduce by additional quarter from 2015 to 2020 [2]. The power conversion unit, specifically an inverter is a core of all PV generation systems to interface with the utility grid for transferring the DC power provided by solar array to an AC output which is connected to the utility system. Considerable research efforts are being conducted for deploying the multilevel and modular-based configurations for photovoltaic power generation networks [3, 4].

The Modular Multilevel Converter (MMC) is a novel topology with distinct characteristics being discussed to implement in large-scale PV structures to meet the requirements as outlined in international standards. Some of these features commonly considered in PV power grids are modular design, high quality of output waveforms, scalability, and fault tolerant capability [4-6]. Grid-connected PV conversion units are sensitive to variations of solar irradiation and weather dynamics due to their inherent intermittent nature. Hence, maximum power point tracking (MPPT) techniques are of great importance to exploit solar panel power with higher efficiently at various working points including atmospheric transients as discussed in [7, 8].

Careful assessment of key requirements associated with solar power production reveals that robustness, high-control bandwidth and tracking accuracy of implemented MPPT schemes have largely influenced the entire PV system efficiency. Among various reported MPPT-based solutions in PV applications, there are several proposals in literature to cope with the deficiencies of the well-established algorithms such as Perturb and Observe (P&O), Ripple-Correlation Control (RCC) and Incremental Conductance (INC) approaches [8, 9]. Special attention has also paid to the hybrid MPPT algorithms to improve e.g., power ripples of each conventional technique [10]. In recent years, further researchers have made a proposals by integrating advanced control methods into MPPT to bring more enhancement and effectiveness for overall PV power station. It turns out that different model predictive control (MPC) arrangements give a promising choice to fulfill the operational criteria described in relevant PV standards [11-13].

In the previously published contributions [11], the PV panel power estimation using predictive control methodology is discussed to alleviate power production changes in grid-tied PV structure committed to the electricity market. However, these types of alternative solutions are heavily dependent on the passive components sizing like capacitance values, which imposing an error on the control system and adding high power variations to the PV modules. Furthermore, the latter designs in [12, 13] have demonstrated significant improvement under fast changing of solar irradiance levels through implementing MPC principle to remove current sensor measurement of PV panels. This proposal is still lacking efficiency degradation assigned from DC-link or inverter stages due to only resistive-load characteristics are considered. As a result, there are a number of open challenges, in particular for large-scale PV power networks that have not been well addressed in the literature.

The contribution of this paper is to explore the opportunities of using optimized-predictive control strategy, while PV MPPT is incorporated into the objective function. Additionally, the modified circuit of MMC topology proposed in the inverter side is also regulated via developed predictive controller comprising other cost function objectives as DC-link voltage and grid current control. The proposed technique uses only PV voltage measurement and thus current sensor is mitigated. Furthermore, another intention of this study lies into employing multilevel power conversion with merits of lessen voltage rating of power switches, reduced cell's capacitor size and DC-link voltage magnitude. These characteristics and the basic idea behind the conversion circuit operation extensively addressed in previous publication [4] and is followed here to reduce the footprint and cost of PV system. Simulation results are presented to investigate the performance of entire PV system with deployed conversion topology utilizing sensorless predictive MPPT algorithm in the presence of solar panel mismatch and during partial shading conditions.

## II. ARCHITECTURE OF PV INVERTER AND OPTIMIZED-PREDICTIVE MPPT DESIGN

The proposed PV system constituting a stacked-multilevel conversion unit and its MPPT strategy is illustrated in Fig. 1. In conventional MMC circuit, both the upper and lower converters should be rated for the nominal DC-link voltage magnitude. In case of existing $n$ half-bridge cells in the upper/lower arms, then each cell must be rated for ($Vpv/n$).

Consequently, the power switches and capacitors formed these cells should be rated for ($Vpv/n$). It is possible to improve this rating by introducing an open-end transformer instead of arm inductors as shown in Fig. 1. This advantages give a doubling of the DC-AC voltage gain, e.g. lead to operating with a lower DC-link voltage supplied via PV array. The detailed analysis of this circuit arrangement in grid-connected PV application is provided in [4].

To regulate the proposed PV inverter stage, the developed predictive controller is assigned to meet two objectives as remaining cells capacitor voltages within tolerable band and grid current adjustment. In this way, large harmonic contents created by PWM switching strategies are mitigated. As mentioned before, third objective included in the cost function is sensorless MPPT scheme, which is achieved through an optimal-MPC formulation considering an integrated perturbation analysis and sequential quadratic programming (IPA-SQP) optimization solver.

The salient feature of merging IPA-SQP solver into cost function tuning process is to make a robust and computationally effective predictive controller in real-time realization [14] for fast response to solar irradiation changes under dynamic atmospheric uncertainties and load shedding impacts. The iterative steps adopted in each sampling time are shown by flow-chart in Fig. 2. Applying Kirchhoff's laws (KVL and KCL) and analyzing the system current and voltages parameters denoted in Fig. 1, the mathematical equations indicating controlled state variables i.e., $i_j$ and $V_{Ci}$ in a bilinear form are governed by:

$$\begin{cases} \dfrac{di_j}{dt} = \dfrac{1}{(L_{trans} + 2L)}\left[ v_{lowj} - v_{upj} - (R_{trans} + 2R)\, i_j - 2V_{grid_j} \right] \\ \dfrac{di_{cirj}}{dt} = \dfrac{1}{2L_{trans}}[V_{dc} - v_{upj} - v_{lowj} - 2R_{trans}\, i_{cirj} - \dfrac{2}{3}R_{trans} I_{dc}] \\ \dfrac{dv_{PV}}{dt} = \dfrac{1}{C} S_i . \left( i_{PV_{ON}} - i_{cell} \right), \quad \dfrac{dv_{PV}}{dt} = \dfrac{1}{C} S_i . i_{PV_{OFF}} \qquad i = 1, \ldots 2N \end{cases} \tag{1}$$

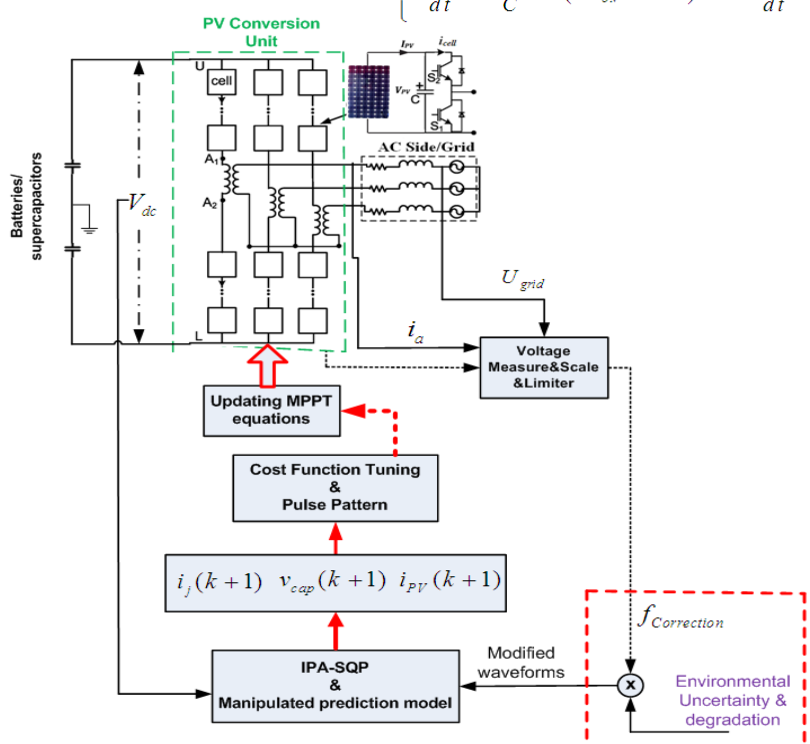


Fig. 1. Structure of a PV plant with predictive controller scheduled by MPPT algorithm involving uncertain parameters.

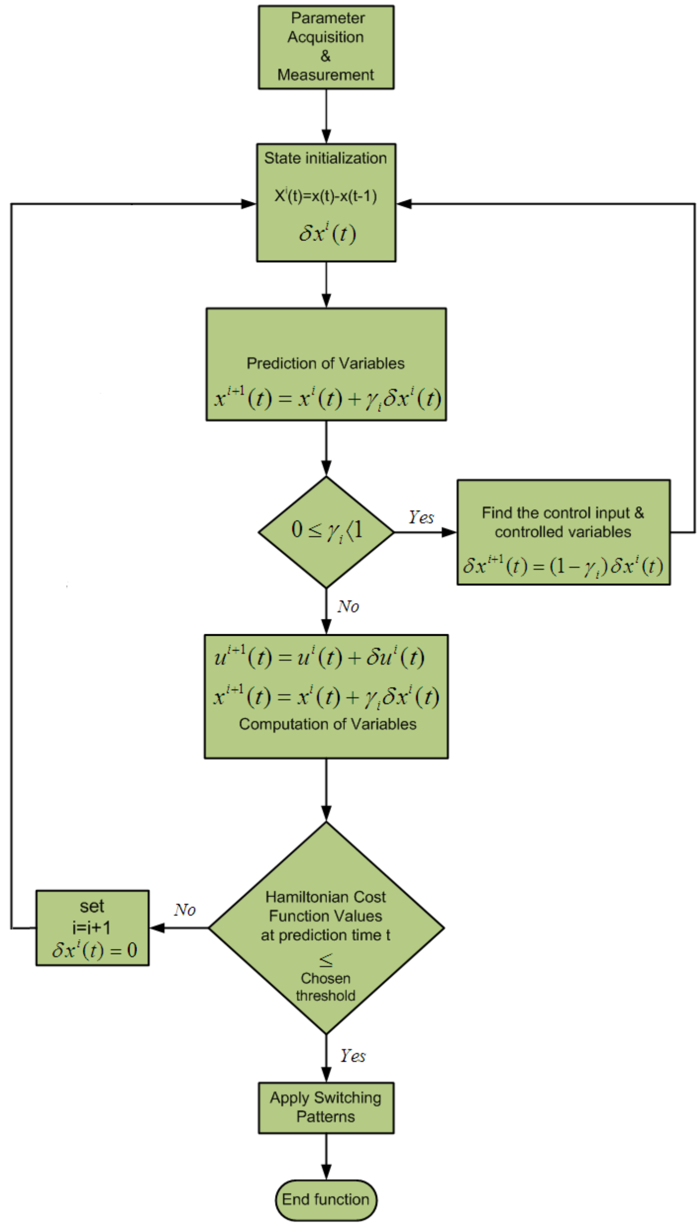


Fig. 2. The IPA-SQP flow-chart employed in each sampling period in terms of a constrained FCS-MPC problem.

where $v_{up}$ and $v_{low}$ are the voltages in upper and lower converters, $L_{trans}$ and $R_{trans}$ represent the transformer inductance and resistance in primary side, respectively. The circulating current flowing through inside the conversion legs is denoted as $i_{cirj}$. Also, $V_{gridj}$ , $L$ and $R$ indicate the grid voltage, grid inductance and resistance, respectively ($j$=$a$, $b$, $c$ phases). $S_i$ indicates the gating pulses for the semiconductor power switches. The number of cascaded cells per leg in the inverter stage is stated by $N$. $i_{PVOFF}$ and $i_{PVON}$ are the PV currents over a control instant where the specific cell is switched-off or switched-on, and $i_{cell}$ is the current flowing through power switching devices.

Note that depending on the operation status in each h-bridge structure for the entire control period, either the turning ON-state cell and turning OFF-state, a prediction model is derived for the PV array current. Looking at Fig. 1, the related expressions can be obtained as presented in third equation term of (1). The controlled variables in (1) are transformed into discrete-time by means of chosen Midpoint Euler for discretization to compute one-step-ahead prediction instant.

It is presumed a grid voltage forced to be constant over sampling period, e.g., $V_{grid_j}(k+1) \approx V_{grid_j}(k)$. Thus, the first two controlled variables are acquired and can be written as:

$$i_j(k+1) = i_j(k) - \frac{T_r}{2\left(L + \frac{L_{trans}}{3} + T_r R\right)}.$$
$$\left[V_{grid_j}(k) - v_{up}(k+1) - v_{low}(k+1)\right]$$
$$v_{C_i}(k+1) = v_{C_i}(k) + S_i(k).\frac{T_r}{2C}\left(i_{cell}(k) + i_{PV}(k+1)\right) \quad (2)$$

where $T_r$ is the predictive time instant. It is useful the input control can be approximated by essential optimum condition for derivative terms and substitution of third equation of (1)

$$\frac{\Delta v_{PV}}{dt} = \frac{\Delta v_{cap}}{T_r} \Rightarrow \begin{cases} \frac{\Delta v_{cap_{off}}}{T_r} = \frac{1}{C} S_i . i_{PV_{OFF}} \\ \frac{\Delta v_{cap_{on}}}{T_r} = \frac{1}{C} S_i . \left(i_{PV_{ON}} - i_{cell}\right) \end{cases} \quad (3)$$

Hence, the prediction equation of the PV panel current over future horizon *k+1* is obtained according to

$$i_{PV}(k+1) = i_{cell}(k) + \frac{C}{2T_r}\left(v_{PV}(k+1) - v_{PV}(k)\right) \quad (4)$$

At this point, the following quadratic objective function *J* is made up of three desired terms subject to optimization yields in (5) to choose the best control actions:

$$J = \gamma_1 . \left| i_j^*(k+1) - i_j(k+1) \right|^2 + \gamma_2 . \left| i_{cirj}(k+1) \right|$$
$$+ \gamma_3 . \sum_{i=1}^{2n} \left| v_{C_i}(k+1) - \frac{V_{PV}^{ref}}{N} \right|^2 \quad (5)$$

It is seen that regulation of the circulating current is also taken into account in fitness function to further reduce converter losses. The weighting factors $\gamma_1$ to $\gamma_3$ are determined dynamically according to IPA-SQP solver.

As described in [15], there is appreciable interaction between the switching frequency variations and switching converters working points, in which this characteristic cannot be eliminated and have to be accounted during tuning process of the cost function.

To meet the major challenge of operation parameters changes, e.g., initial conditions, this paper has deployed an SQP update procedure based on linearization and quadratic cost approximation to overcome the limitation of a perturbation analysis (PA) to predict a change in the optimal solution. Considering synergetic merging of these two approaches, the optimal control sequence per sampling instant *t* along with the controlled state *x(t)* is computed via the optimal control sequence from the previous sampling instant (*t-1*). In doing so, a closed-form and efficient formulation for the intended optimization are achieved. Fig. 2 presents the detailed steps of how the IPA-SQP algorithm is executed and combined with the MPC problem.

## III. SIMULATION RESULTS OF THE CASE STUDY

The PV system comprising a 5-level modular conversion topology formed by series connection of four H-bridge cells, in which each has one PV panel is implemented using MATLAB/SIMULINK software package to verify the theoretical findings. The detailed circuit specifications are tabulated in Table I.

TABLE I. PARAMETER RATED VALUES OF THE SIMULATED PV SYSTEM

| | | | |
|---|---|---|---|
| PV array rated power | 200 W | Solar array current (max) | 5.71 A |
| Solar array voltage (max) | 35 V | Cell capacitance | 2.2 mF |
| DC-link voltage | 140 V | Grid voltage | 120 V |
| Number of PV inverter cells | 4 | AC line inductor | 3 mH |
| Transformer resistance | 0.074 ohm | Output frequency | 50 Hz |
| Transformer inductance | 3.48 mH | Sampling time | 25 μs |

The developed PV panel considered in this study is based on the given specifications for the commercial PV array from Kyocera KC200GT [16]. Fig. 3 shows the *I-V* and *P-V* characteristic curves utilized for the modeled conversion modules containing PV panels.

The steady-state evaluation is performed when all the four PV arrays working in normal conditions within their voltages and currents at maximum power points. Fig. 4 shows the measured PV power extracted from four solar panels and compared with the reference value indicating acceptable power tracking behavior with developed control strategy.

Another operating scenario is that the three PV panels in each phase having a different irradiation slopes varying from 300W/m$^2$ to nominal 1kW/m$^2$ due to the sun light conditions. The fourth PV panel functioning with nominal irradiance level 1kW/m$^2$. Fig. 5(a) and (b) present the waveforms of the total DC-link voltage in phase-A and current waveforms for the considered three PV panels under irradiation ramp changes.

Fig. 6 presents the inverter line voltage in phase-A. It is proved that the line voltage magnitude is higher than the provided DC-link magnitude through PV arrays as described by the theory in [4].

A fair judgment is also made by comparing the performance of the two widely used MPPTs; P&O and RCC with the proposed one while the irradiance levels varying.

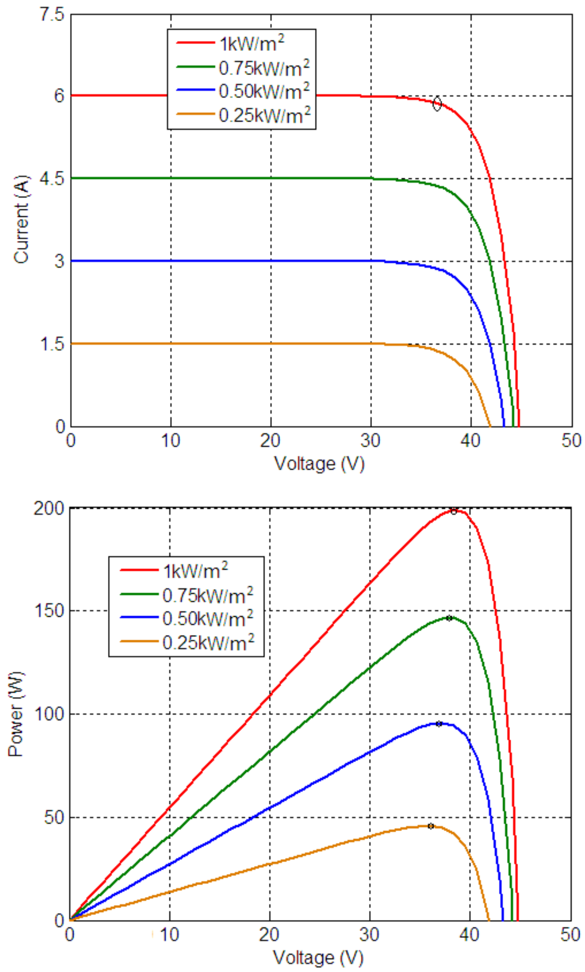


Fig. 3. Current and power versus voltage curves of the studied PV panels at different illumination levels.

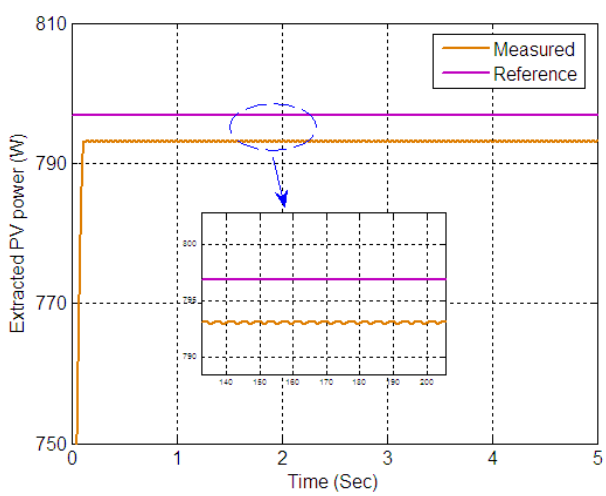


Fig. 4. Obtained power from PV panels in steady-state operation.

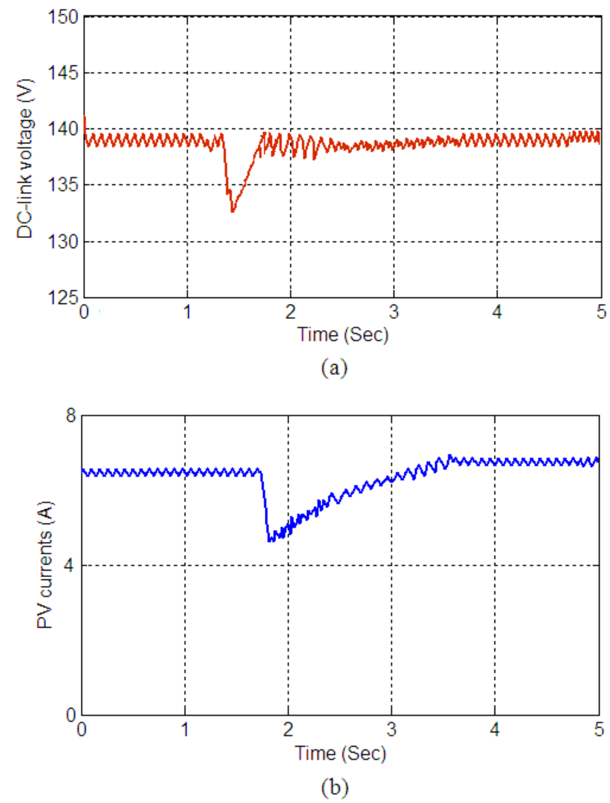


Fig. 5. The response of optimized-predictive MPPT controller under ramp variation of three-PV panels at t=1.6sec; (a) DC-link voltage of phase-A, (b) Currents for three PV panels in phase-A

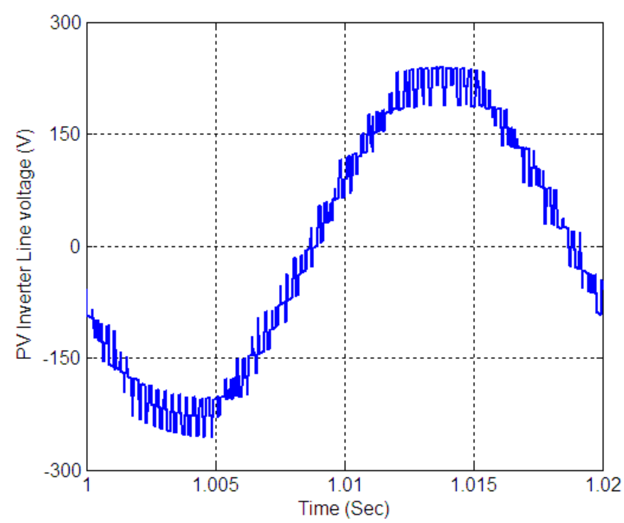


Fig. 6. Simulated Line-to-Line voltage waveform in phase-A for the proposed PV inverter.

Fig. 7 illustrates the comparison outcomes, where the P&O and RCC MPPTs have applied earlier to the same PV inverter in [4] and [17], respectively. From Fig. 7, higher tracking efficiency is achieved by the suggested sensorless MPPT technique under wide range of solar irradiation changes.

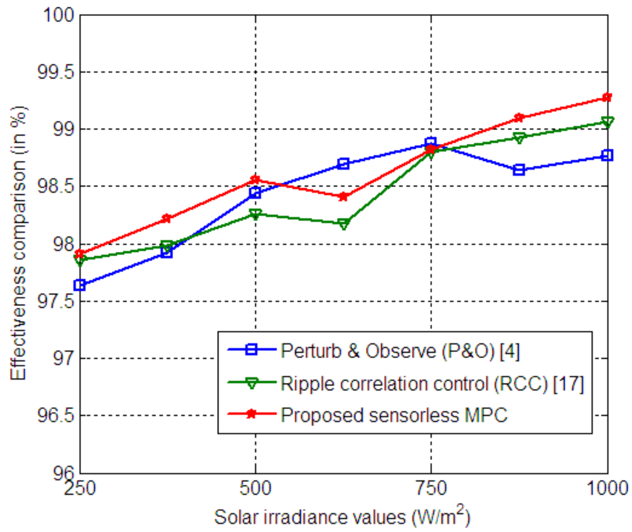


Fig. 7. Compared control efficiency of three different MPPT schemes for the same PV conversion topology.

In summary, acceptable performance of the proposed predictive-MPPT strategy without PV current sensor is achieved together with the benefits of proposed PV conversion circuit. It is planning to compare the results of the discussed strategy with the existing MPPT methods in terms of real-time realization on an available embedded hardware. This is the subject of future researches.

## IV. CONCLUSIONS

This paper revealed the operation performance of a MPPT approach based on optimized-predictive control design for grid-connected stacked multilevel photovoltaic inverter. The discussed MPPT scheme is capable of handling system uncertainty with unknown parameters like aging solar arrays, efficiency degradation and partial shading conditions. From a real-time realization perspective, the proposed control arrangement can be implemented with high-speed tracking on an embedded platform because of integrating an IPA-SQP solver into the MPC optimization problem which gives a lower computational burden. Additionally, with the aim of deployed power conversion topology incorporating energy storage elements, the capacitor size and total rated value of the DC-bus provided by PV panels is effectively reduced, while producing the same output voltage level as the existing cascaded-based PV inverters. The main findings are validated through the simulation results for a PV system with a 5-level PV inverter with respect to fast power tracking and solar irradiance disturbances.

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