Coordinated Stability Assessment of Power Converter in Electric Vehicle Charging Station Using Predictive Control Reconfiguration

Hamed Nademi, *Senior Member, IEEE,* Kourosh Sedghisigarchi[*], *Senior Member, IEEE,* and Luigi Vanfretti, *Senior Member, IEEE*

Rensselaer Polytechnic Institute, Troy, NY 12180 USA
[*]California State University, Northridge, Northridge, CA 91330 USA

***Abstract*—Power conversions deploying in fast charging stations of electric vehicles (EVs) are vulnerable to instabilities during certain operating conditions. Additional connected loads for charging large number of EV batteries can compromise the whole system reliability and impose thermal stress on the storage device/ generation sources interfaced on the common DC-bus system. Stability assessment by small-signal impedance measurements are not necessarily efficient to predict large-signal stability characteristics. This study addresses a robust and optimal control scheme to overcome instabilities in different operating conditions when Vehicle-to-Grid technology is incorporated. An integrated perturbation strategy with sequential quadratic optimization (IPSQO) algorithm is applied to optimize the charging load of EVs and achieve the peak shaving load. Outcomes of case study analysis are provided to verify the proposed control strategy effectiveness.**

Keywords—charging station, electric vehicle, harmonic distortion, perturbation and sequential quadratic programming, predictive control, stability analysis.

I. INTRODUCTION

With increased environmental protection problems, electric vehicles considerably attracted both the industry and academia attentions because of offering energy conservation and environment-friendly characteristics. Electric Power Research Institute (EPRI) predicted the different types of electric vehicle technologies would shift the level of penetration up to 62% by 2050 in the U.S. [1]. Promising solutions for fast charging stations of electric vehicles (EVs) are still demanding with stability considerations of their interfaced requirements on the AC distribution network. An integrating periodic loads with different energy storage technologies to the common DC bus is strong alternative to the existing infrastructures. Due to the inherent feature of the loads connected to the charging stations similar to a constant power load (CPL), the steady input impedance (resistance) is negative that leads to an instability of the connected system, e.g., common DC-bus destabilization [2]. Consequently, there is more likely instability issue for the conversion system operation arising from loads.

A significant R&D challenges are still uncovered for practical applications considering nonlinearities appear from various sources, models and control designs.

Small-signal analysis, in which gives a constructive insight for stability around equilibrium point, have been mostly on the focus of the researcher, thus addressed several challenges by developing new theories. Those theories have already adopted in industry and presented an acceptable performance without any failure. However, the boundary conditions of the stability region to comprehend system response in the case of large perturbations, e.g., short-circuit fault is of great importance. Small-signal stability modeling and linear controls are unable to provide nonlinear theoretical analysis with helpful dynamic responses [3] during large transients happening to the power system. Passive and active stabilization methods have also drawn research attention, although the latter favored method heavily uses small-signal and Nyquist criterion, but it becomes problematic as far as large signal stability concerned [2].

Furthermore, in the case of transient stability, well-equipped converters with superior ride-through functionality are deemed to strengthen the protection system with key challenges still remaining unsolved. Over the last years, R&D organizations together with industries have found that analysis of the aforementioned phenomena requires the electromagnetic transient (EMT) models catering for frequency spectrum of interest that would allow key stability modeling, performance analysis and control strategy development as well as design adjustments to be carried out effectively. Within these efforts, several drawbacks have been identified with impedance stability evaluation technique employed based on dq-reference frame, highlighting the need for sequence impedance method in frequency-domain as discussed in [4]. With this in mind, it has been deduced that for a proper operation of future power grids with various renewable energy resources, there would be a need for both small-signal and large-signal methods to be considered to ensure the full operational dynamic of the network is fully understood.

The existing techniques for large-signal stability analysis have been compared in [5], [6]. This have shown to reach asymptotic regions of stability and concluded that most of the proposed approaches cannot be employed for constrained dynamic systems such as wind energy systems. Techniques concerning Lyapunov-based theory demonstrate stability evaluation of a dynamical and complex system including stability criteria independent of the need for differential equations numerical solutions [7]. The key difficulty in this kind of stability assessment is to develop helpful candidates for Lyapunov function in a systematic manner. As addressed in various earlier studies, the analysis results might be either applicable to some limited applications or resulting conservative findings.

A proposed control scheme comprising two-layer configuration is presented in this paper, for which a first-layer finite control set-model predictive control (FCS-MPC) methodology provides initial controlled variables to regulate the rectifier module voltages and currents at the connected loads. Most of the existing stabilization methods are linear control methods. These are based on small signal models and theoretically could only ensure small signal stability near the operation point. Therefore, an existing linear stabilization methods may be ineffective to fix large-signal stability issues. The instability is observed through the operational performance of the Modular Multilevel Converter (MMC) deployed to transfer AC power generated by medium-voltage grid to common DC bus feeding multiple EV batteries.

The second-layer iterative controller is embedded into an integrated perturbation analysis and sequential quadratic programming (IPA-SQP) algorithm for handling nonlinearities, updating weighting factors and sensitivity analysis.

This work is an extension of developed the representative mathematical models of the AC grid side in [8], so as the dynamic common DC-bus equations will have to be incorporated into the analysis since we would need to develop the entire system model to apply the proposed control strategy and stability analysis.

According to the Lyapunov criteria, the proposed predictive scheme derives the large signal stability constrains in a clear way and maps them across to the analytical results, then subsequently adds them to the cost function of the MPC method. In this approach, the stability constrains of the proposed control method would not need to select the weight of the stability in the cost function compared to the existing MPC method. The demanding control solutions have to be less intuitive to satisfy stringent industry requirements such as computational encumbrance and application flexibility. Most control objectives are gradually improving the computational challenges associated with variables constraints, lowering the DC ripples and grid current harmonic contents. The feasibility assessment of load-leveling approach is also studied when large energy storage systems are in operation. To prove a functionality of the proposed design, numerical simulations are conducted and exemplary results are presented.

II. STRUCTURE OF FAST CHARGING STATION WITH PROPOSED POWER RECTIFICATION UNIT

The discussed electric vehicle (EV) fast charging station is made up of power conversion as shown in Fig. 1. This consists of two stages, where the first AC-DC stage is interfaced to the MVAC distribution network based on full-bridge MMC as illustrated in Fig. 2(a). Additional functionality is devoted to voltage support on the grid in case of operation with large connected energy storage devices.

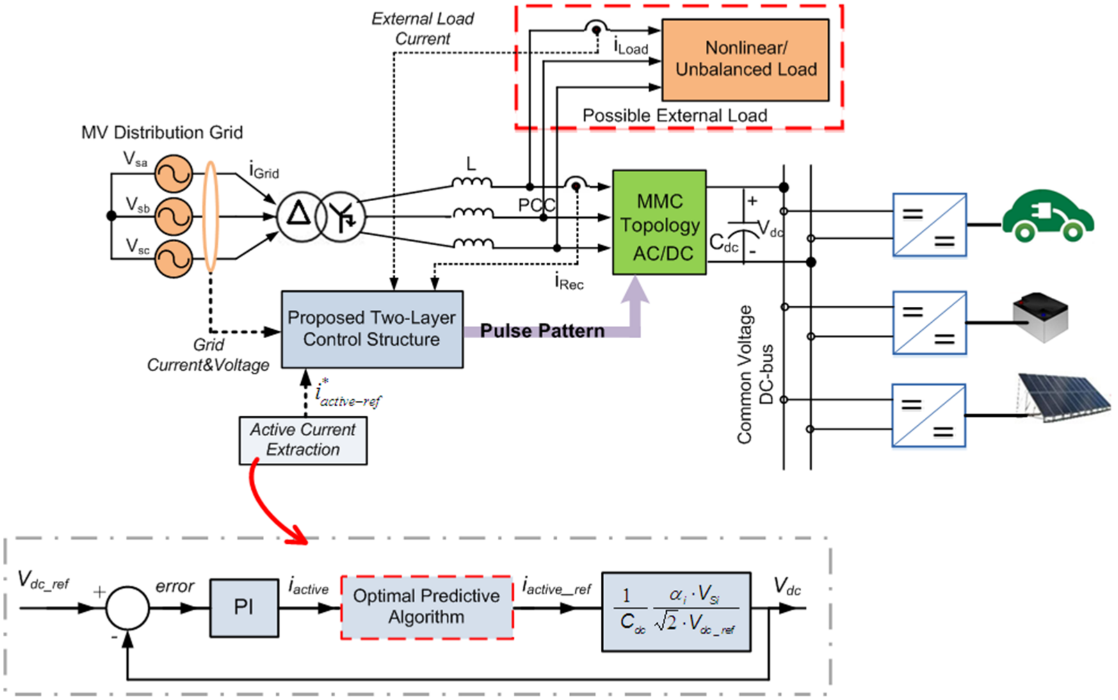

Fig. 1. Typical fast-charging station configuration connected to the distribution grid via proposed optimized predictive control structure.

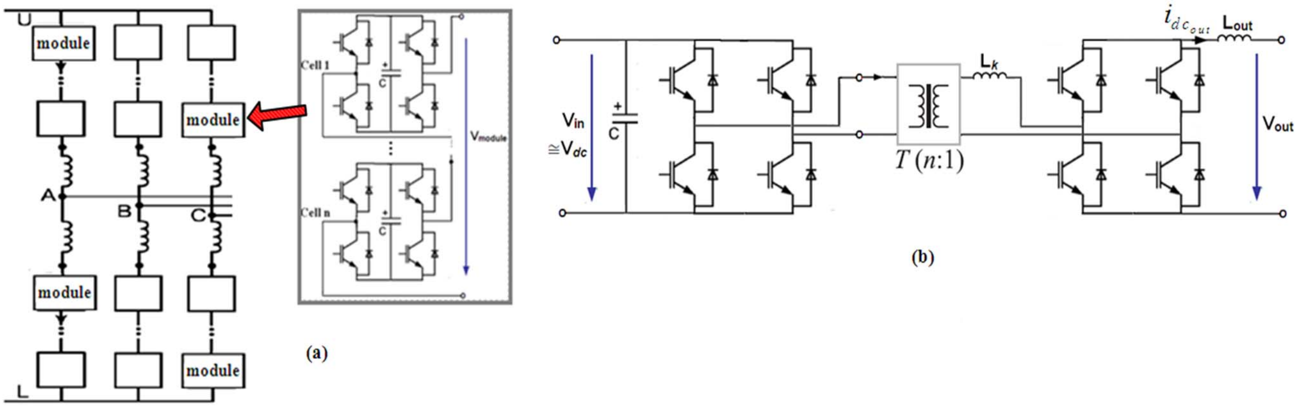

Fig. 2. Structure of (a) MMC rectification unit, and (b) current-fed dual-active bridge DC-DC converter.

The second stage using DC-DC converter is parallel connection to the common DC-bus to supply several loads such as feeding electric vehicle battery, energy storage device and multiple distributed generation resources, e.g., solar PV. As indicated in Fig. 2(b), a current-fed modular dual active-bridge (CF-DAB) DC-DC converter is designed which includes full-bridge architecture interfacing through a medium-frequency (MF) transformer. This structure capable handling the bidirectional power flow along with the provided galvanic isolation offering V2G technology to support AC grid through EV battery, and lowering fluctuations in the charging/discharging currents reflected at the storage device. Thus, wide operation with variable voltage conversion rating, of which is more compatible to the battery charging process is achieved [8], [9]. This study presumes n=2 modules per converter leg constructing 12 modules in the entire rectification unit. Employing KVL to AC-DC conversion unit in Fig. 1 deduces the equation (1):

$$V_{sa} - V_{\mathrm{Rec}} = R.\,i_{\mathrm{Rec}} + L.\frac{di_{\mathrm{Rec}}}{dt} \tag{1}$$

V_{sj} is the distribution grid voltage, V_{Rec} represents the MMC terminal voltage at AC side which is formed by summation of all modules input voltages in respective phase. L is the equivalent grid inductance in addition to step-down transformer leakage inductance. The current following through each *n-th* module, $i_{O\ modulei}$ ($i=1,\ldots n$), has a relation with the input rectification AC side current i_{Rec}.

III. DEVELOPED LARGE-SIGNAL STABILITY SOLUTION BASED OPTIMIZED PREDICTIVE CONTROL

Transformational trend of emerging power grids enables control solutions to be equipped with distinctive features such as low computational burden, high flexibility for easily realization on different built-in manufacturer's design to meet the industry requirements. Innovative control solutions should be considered and introduced for various operation modes from normal conditions to large disturbances. The demanding solutions will unavoidably require the important converter and dedicated control subsystems nonlinearities (including DC-link voltage and PLL dynamics, control delay, switching process) to be fairly incorporated into design and modeling processes.

This technique would be effective when a stability region is time varying and have a converging narrow time window. However, for large-scale wind power grids, there are open challenges to be addressed. Predictive control models tend to handle nonlinearities fairly well and tended to account for constrains on variables which are included in the intuitive predictive procedures [10]. It is more beneficial to synthesize cost function based on Lyapunov stability theory, to guarantee satisfactory performance of local control system in a large signal sense.

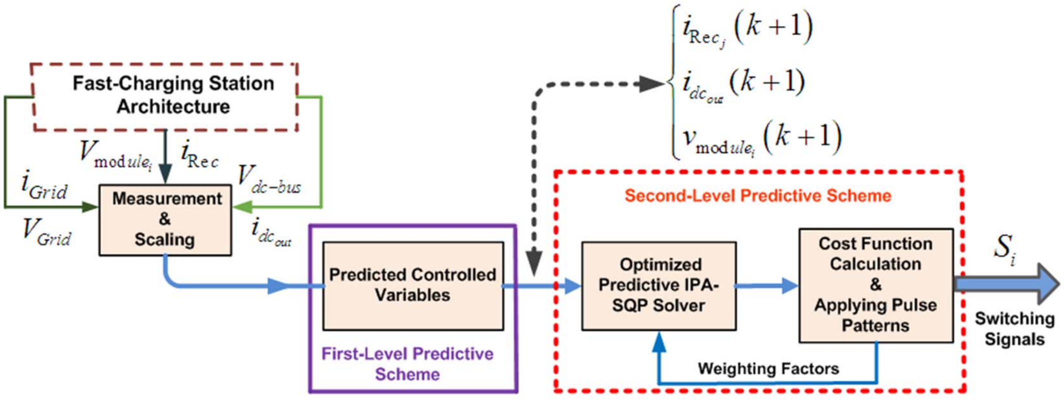

Fig. 3. Configuration of a two-level predictive control strategy producing the optimal pulse patterns for power conversion unit.

Based on derived mathematical equations in [8], the discretized expressions of the state and input variables for a one-step ahead prediction horizon are shown (*j*=phase *a, b,c*):

$$
\begin{aligned}
& i_{\mathrm{Rec}_j}(k+1) = i_{\mathrm{Rec}_j}(k) - \frac{T_s}{2\left(L + \frac{L_{arm}}{3}\right)} \\
& .\left[V_{Sj}(k) + v_{upper}^{j}(k+1) - v_{lower}^{j}(k+1)\right] \\
& i_{dc_{out}}(k+1) = i_{dc_{out}}(k) - \\
& \frac{1}{T_s}.\left[\frac{V_{\mathrm{Rec}_j}(k)}{L_{equ}}.S_i(k) - \frac{V_{out}(k)}{L_{out}}\right] \\
& v_{\mathrm{mod}ule_i}(k+1) = v_{\mathrm{mod}ule_i}(k) + \\
& \frac{S_i(k).T_s}{2C_{\mathrm{mod}ule_i}}\left(i_{\mathrm{Rec}_j}(k) + i_{\mathrm{Rec}_j}(k+1) - i_{O\,\mathrm{mod}ule_i}(k)\right)
\end{aligned}
\tag{2}
$$

Where T_s is the sampling time instant and L_{arm} represents the converter arm inductance. V_{upper} and V_{lower} are the voltages of the upper/lower cells in the converter. V_{module} denotes the total voltage level of all cluster cells per phase. V_{out} , I_{dcout} and L_{out} are the output DC voltage, current, and inductor of dual-active bridge converter, respectively.

The quadratic cost function *J* to apply an optimized switching states including design constraints and stability criteria is defined by

$$
\begin{aligned}
J = {} & \alpha_1 . \left\| i_{\mathrm{Rec}_j}^{ref}(k+1) - i_{\mathrm{Rec}_j}(k+1) \right\|^2 + \\
& \alpha_2 . \sum_{i=1}^{n} \left\| v_{\mathrm{mod}ule_i}(k+1) - V_{\mathrm{mod}ule_i}^{ref} \right\|^2 + \\
& \alpha_3 . \left\| i_{active}^{ref}(k+1) - i_{dc_{out}}(k+1) \right\|^2 + \left| \underbrace{\dot{V}_{Lyapunov}}_{Stability} \right|
\end{aligned}
\tag{3}
$$

The weighting coefficients α_1, α_2 and α_3 are calculated from SQP numerical algorithm systematically to reduce the effects of uncertainties and constraints in the control loops. From the Lyapunov criteria, the developed predictive scheme presented in Fig. 3 derives the large signal stability constrain in a clear way and transfers it to the analytical results, then adding it to the cost function of the MPC method. The stability constrains of the proposed control method does not need to select the weighting factor of the stability in the cost function compared to the existing MPC techniques.

A detailed process of the IPSQO technique formed of predictive cost function and stability formulation is shown in Fig. 4. The optimal control sequence *u*(*k*) is extracted upon fulfilling the conditional stability expectation and cost function adaption *J*(*k*) to achieve control objectives.

For handling of appeared uncertainties in the system and achieve an intended optimal solution as demonstrated in the flowchart, if at the point $x^i(t)+\delta x^i(t)$, where *i* is the iteration index, the Hamiltonian function (4) against the control state *u(t)* is not small enough at prediction time *k*, hence the iterative procedure gives zero initial state perturbation $\delta x^i(t)=0$. For further reading and description we reference to [11], [12].

$$
\sum_{k=t}^{t+N-1} \left\| H_u(k) \right\| \neq 0 \tag{4}
$$

IV. SIMULATION RESULTS OF THE CASE STUDY

In this section, simulation analysis for a power converter deployed in fast charging station with circuit parameters are given in Table I will be discussed. In conventional PWM strategies, due to the converter switching frequency, e.g., 5kHz, the frequency of the switch current ripple is the same as well. The voltage loop bandwidth for the rectifier is much lower than 5kHz, and the common DC-bus voltage fluctuation has a strong relation to the common DC capacitor size. For the sake of entire system function safely, the maximum DC-bus voltage is chosen to be less than 700V. Moreover, the capacitor voltage variations can cause an unbalance issue reflected in the input current of the rectifier, resulting in transient instability condition.

The numerical simulation result in Fig. 5 illustrates there is current imbalance condition in the AC currents of the rectifier. The performance of the proposed design with stability constrain is evaluated when oscillations occurred in the common DC-bus leading to unstable system. In this case scenario the stability loop of the converter controller is activated at time instant t=0.7sec.

TABLE I
PARAMETERS USED IN SIMULATION ANALYSIS

Parameters	**Value**	**Parameters**	**Value**
Full-bridge cell in each module	2	DC-bus voltage	600V
AC voltage	13.8kV	Capacitor voltage setpoint per module	150V
Grid transformer	350kVA, 13.8kV/400V	DC inductor	1.7mH
EV battery capacity	450V, 20kWh	Sampling time	25 µs
DC-DC converter power	80kW	MMC arm inductance	3mH
Leakage inductor	0.22mH	MMC cell capacitance	3.3mF

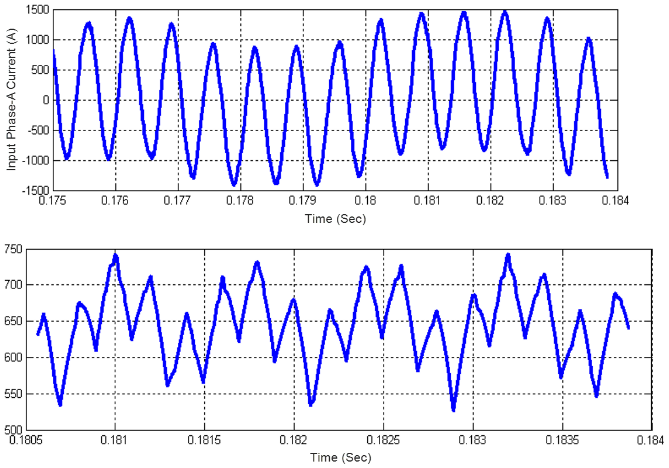

Fig. 5. Instability issue of current waveform caused by the voltage variations on the common DC-bus observed in an exemplary operating condition.

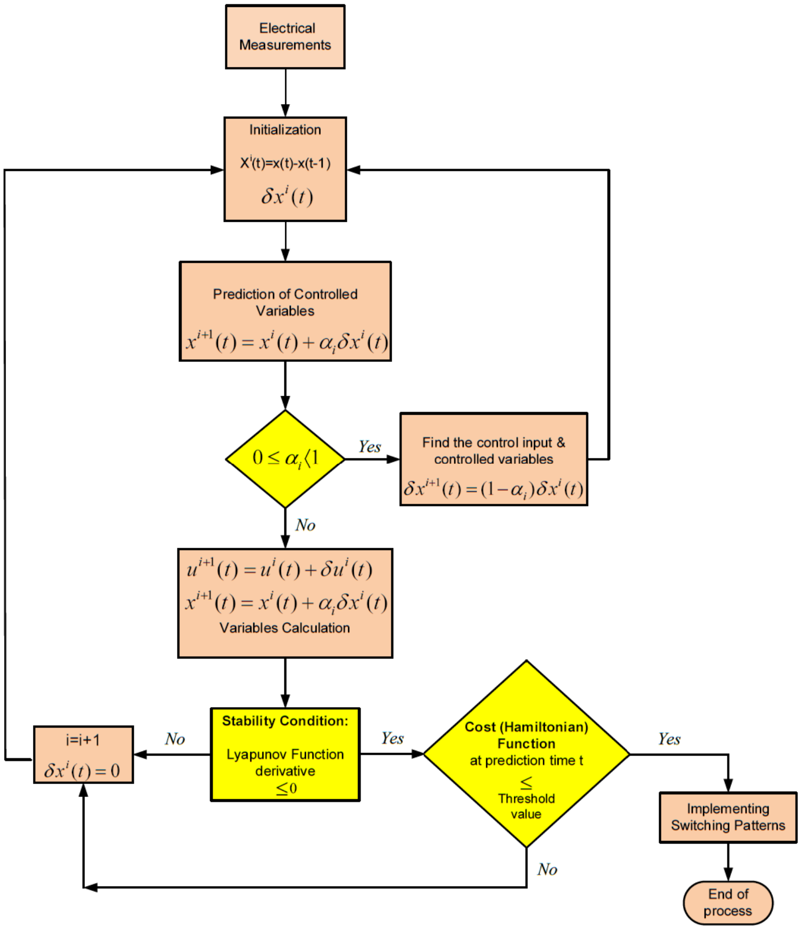

Fig. 4. Optimization process implemented in each sampling period including predictive formulation and stability constrain.

Fig. 6 shows the DC-bus behavior before this time, when the stability constraining feature enables a stable response of the DC-bus again. The line current in phase-A is also presented verifying an acceptable input current waveform. Having included the stability loop function in the predictive controller, such distortions are appreciably eliminated to a desired levels without placing an excessive filters as damping element necessary in passive methods.

According to [13], the THD level should be less than 7% imposing the DC-link voltage level selection in light of this requirement. This demanding requirement calls for control solutions that reduce the harmonics and resonances for charging stations, while satisfying the required complexity and accuracy. Hence, the case scenario is evaluated when unbalanced load is connected into the system. In this example, the damping harmonics feature of the converter controller is activated. Fig. 7 shows the THD levels of the line current in the system when different unbalanced load currents injected. It is observed that the THDs are within the standard recommendations showing satisfactory operation of purposely-designed feature of the controller.

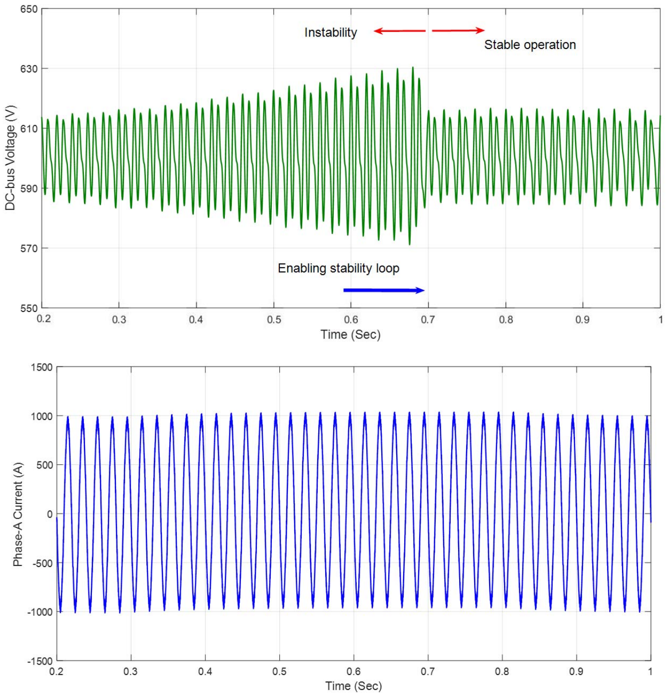

Fig. 6. Comparative waveforms of the common DC-bus and AC current with and without enabling stability feature of the predictive controller.

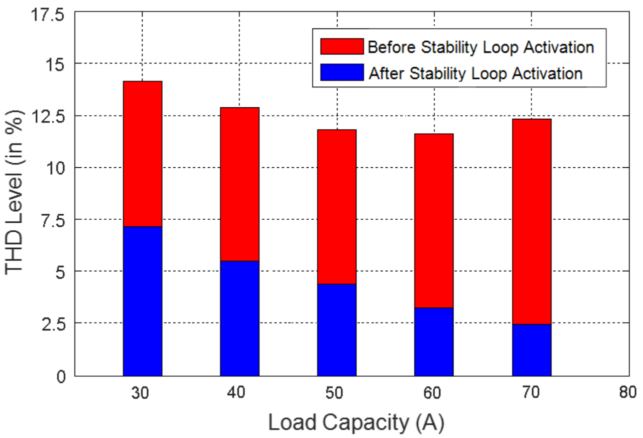

Fig. 7. THDs of the AC line currents compared with and without enabling stability feature of the predictive controller in different load capacities when connected as external unbalanced loads.

V. CONCLUSION AND FUTURE WORKS

Penetration of power converters into fast charging stations alongside of other renewable power generations has resulted in transformative trends in hybrid AC and DC grid system requirements. To achieve satisfactory operation of the entire system, there is a need for new tools for stability modeling with key emphasis on control strategy development. The large disturbances system characteristics are seldom studied comprehensively for DC microgrids prior to installation phase which leads to costly instability problems. In addition, there is a huge demand for advanced control methods development to deal with the both transients and nonlinearities which tend to arise from control loop interactions for system stability purposes. Developed predictive control integrated with optimization programming solution is studied to fulfill EV charging station requirements in different operation modes. Contributions provided by this solution are related to the grid support functionality for reactive power and harmonics damping on distribution grid that will be further explored using real-time simulations. This paves the way for feasibility analysis of load-leveling concept when the system equipped with large number of energy storage devices. An exemplary electric vehicle charging station is presented and its performance characteristics are discussed with respect to harmonics and control nonlinearities.

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