Design of a closed-loop autotune PID controller for three-phase for power factor corrector with Vienna rectifier

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ABSTRACT

A closed-loop auto-tuner proportional integral derivative (PID) controller for tuning the DC-link voltage, voltage neutral controllers, and DQ axis current for a power factor corrector with Vienna rectifier is developed and discussed in this study. In traditional tuning of these control loops, it is needed to tune one loop at a time manually, which tends to be a difficult and time-consuming process. In this work, we add a closed-loop PID auto-tuner in the control design will help to simplify and speed up this process by tuning all the 4 PID controllers in a single simulation running in a closed loop. Essentially, it runs auto-tuning experiments for the DQ axis -current, output voltage, and neutral point voltage loops by injecting perturbations; recording the output; estimating the plant frequency response, and tuning the PI controller parameters. In DQ-axis control, projections are used to convert time-based3-phase currents into a time invariant 2-coordinate vector. The results after adding the auto-tuner show that the response time improved considerably when the balanced load was introduced with the individual loads being connected. The results show that the neutral point voltage controller did a good job of keeping the voltage neutral point stable compared to the older controller gains.

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1. INTRODUCTION

Non-cascaded multilevel inverters (MLIs), such as neutral point clamped (NPC) inverters, are widely used in industrial applications due to their greater voltage ratings, lower device stress, lower harmonic distortion, and cost-effective passive (non-isolated) DC supply [1]. The usage of multi-winding transformers is eliminated with a non-isolated passive DC voltage source, it is prone to other issues [2]–[4].

The following are the three primary issues with such schemes; i) approaches to voltage balancing of the inverter side at the expense of higher commutation control complexity, which are expected to limit MLI operations and rise switching losses [5]–[7]; ii) it has been demonstrated that voltage balancing is impossible for MLIs with more than three voltage levels under certain load situations [8]; iii) appropriate steps must be adopted to reduce harmonics of the grid region current. The usage of passive filters based rectifiers has the potential to degrade system performance. In a DC-bus non-isolated N-level, entire capacitors of N-1 are staked to create the N-1 partial voltage (PV) necessary for the MLI's source [9]. PV is able to be organized by either the rectifier active part (active PV) or the inverter passive PV side. The active technique is preferred whilst power factor correction (PFC) is essential as well. Solutions of 3-phase PFC rectifiers previously offered were primarily restricted to three-level DC output levels [10]. The majority of these 3-levels PWM rectifiers are varying according to Vienna rectifiers (VRs), a widely used 3-levels PFC-activated three-phase front-end solution that was initially designed for telecommunication systems [11].

Generally speaking, the main problem that restricts advanced optimization algorithms from getting good results is that the tuning of control loops is required to tune one loop at a time manually, which tends to be a difficult and time-consuming process, especially in the traditional tuning of these control loops. To deal with this issue, the paper [12] developed a 4-levels PWM rectifier and was the first to examine such a PWM-based 3-phase rectifier with an N-level (N>3). The majority of solutions of earlier initiated multilayer rectifiers (MLR) were limited to up to 5-level or either single phase, for example, the MLR introduced by [13]. This MLR is a typical NPC-based converter including a secondary voltage matching circuitry. There has yet to be offered a genuine self-governing MLR system with more than two output levels. One of the drawbacks of PWM MLR converters is that simple carrier-depend current management via carrier wave scan with grid voltage-based instructions is not possible since accessible switching states are dependent on grid current directions [14]. While active PFC is typically limited to rectifier part current management, PVB-based control is able to be accomplished via either inverter or rectifier controller. A joint of the Back to Back Inverter/Rectifier controllers were also investigated [15], but it lacks adaptability because it cannot be utilized with loads of non multilevel inverters.

PV is capable of performing with no changing the control system of MLI, for example, by employing a secondary balancing circuit (diodes, switches, and inductors) [16]. This method has a number of drawbacks, including increased additional power losses and complexity owing to the secondary components. PV can be obtained through inverter side controlling like optimal-redundant state-selection [17], [18], when a passive MLR without PWM is utilized; nevertheless, as earlier stated, PV cannot be assured at particular operating situations at N>3 [19], [20]. Furthermore, Optimal-Redundant state selection may degrade MLI-based performance by restricting switch-state selection freedom, increasing switching losses, and degrading the quality of output voltage, where redundant switching states were employed for PV rather than output waveform determining) [21]. Another PVB solution for passive rectifiers is to add appropriate offset voltage of a common mode to the three MLI AC voltages reference through the modulation method [22]. This strategy adds to the control schemes of MLI's complexity and might jeopardize its performances.

In this work, an improved closed-loop autotuner proportional integral derivative (PID) controller to tune DQ axis current, voltage neutral, and the DC-link voltage controllers are proposed for the optimization of the triple closed-loop PI controller parameters for a power factor corrector with a Vienna rectifier three-phase PFC converters mitigate most of the aforementioned issues. The closed-loop autotuner PID controller solution is used to avoid the difficulty of PID parameters selection and to achieve a unity power factor, zero steady-state error, and fast transient response. When compared to the conventional PID controller, the proposed Autotuner PID controller improves the global searching ability and reduces the time consumption. Simulation results verify the superiority and effectiveness of the presented method.

2. METHOD

This work discusses how can automatically fine-tune controller loop gains for a DC- link voltage, neutral point voltage, and current controllers for a power factor corrector with Vienna rectifier. In the closed-loop simulation model, the plant model, contains the Vienna rectifier and a switched mode power supply (SMPS) to generate a 400V DC supply from a 3-phase 110V AC power for different loads, the block diagram showing the main components of the system is depicted in Figure 1, while the recognition for the physical and controller components is shown in Figure 2. The feedback compensators subsystem of the switched-mode power supply contains 4 control loops: 2 for tracking the reference DQ-axis currents, one for tracking the DC-link output voltage, and one neutral point voltage control loop to maintain the DC-link capacitor voltages.

In traditional tuning of these control loops, it is needed to tune one loop at a time manually, which tends to be a difficult and time-consuming process [23]. The initial PID controller gains do not provide a good tracking performance. Therefore, adding a closed-loop PID autotuner in the control design will help to simplify and speed up this process by tuning all the 4 PID controllers in a single simulation running in a closed loop. It is essentially to run auto-tuning experiments for the DQ axis-current, output voltage, and neutral point voltage loops by injecting perturbations; recording the output; estimating the plant frequency response, and tuning the PI controller parameters [24].

In tuning cascaded feedback loops. First, the inside current controller is fine-tuned, next, the controller of DC-link voltage and that of the voltage neutral. Because the PID closed-loop auto-tuner can just tune single PID blocks over one time, each of the model's four controllers should be adjusted independently [25]. With the D-axis current control loop, we will place the PID auto-tuner in between the controller output and the input to the plant, which allows the auto-tuner block to inject a sinusoidal-based perturbation signal at the input of the plant and measure the resultant closed-loop plant output through performing the experiment. The MATLAB based simulation diagram is shown in Figure 3(a), while Figure 3(b) shows the D-axis current control loop with its PID autotuner.

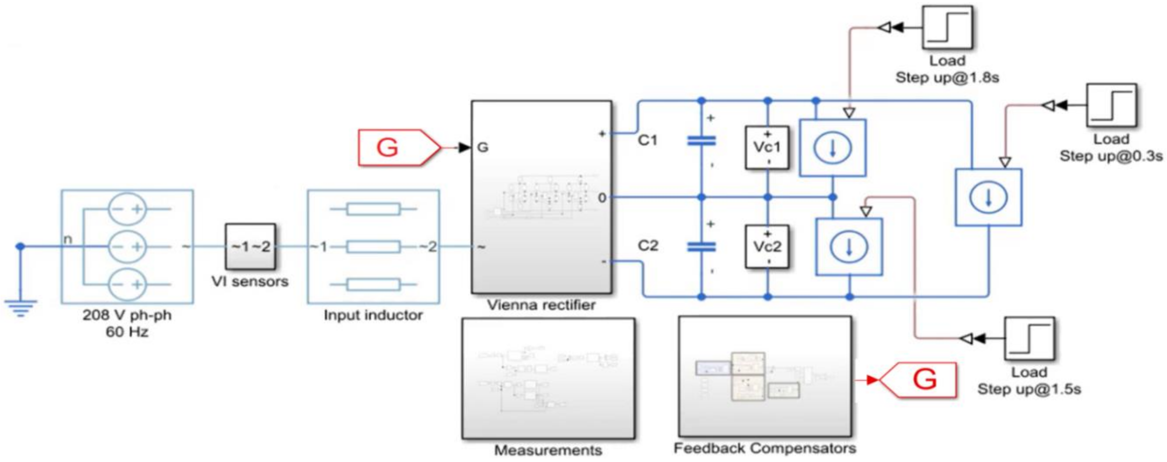


Figure 1. 3-phase 120V to a regulated (400V) DC of power factor corrector with Vienna rectifier

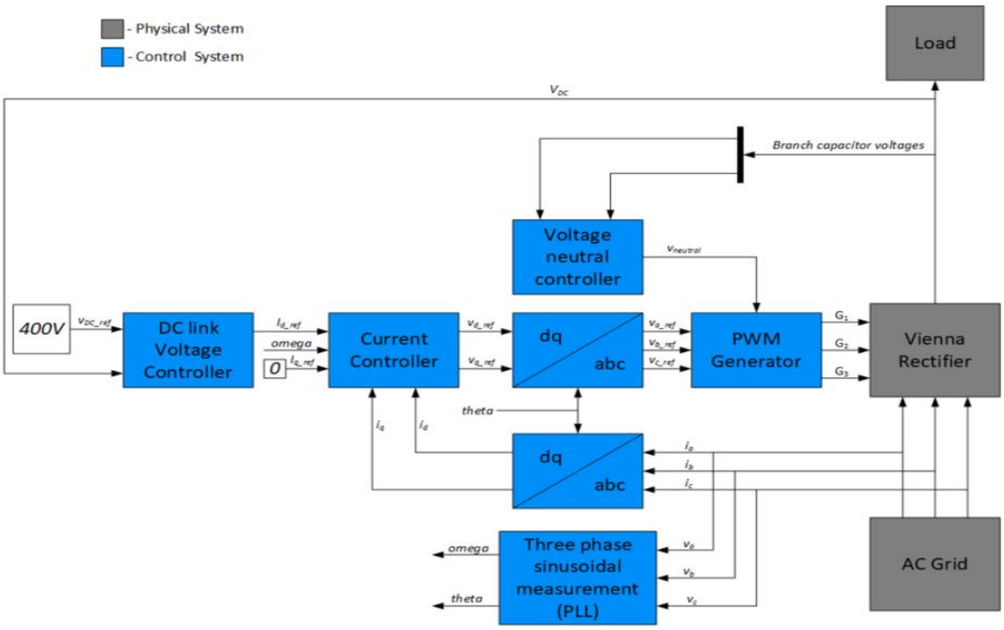


Figure 2. Physical and controller components of the system

At the end of the experiment, the autotuner calculates the gain of the PID controller using a small number of frequency points around the target bandwidth to approximate the plant frequency response. We can then update these gains in the respective PID controller blocks. With the block placed, in the block dialog of the closed-loop PID autotuner block, under 'tuning' we will set a target bandwidth of around 3000 rad/s with a target phase margin of 60 degrees. Under the experiment section, for the current loop, the plant type is stable with a positive sign. We will set the sine amplitudes of the perturbations to 0.6.

There is no exact formula behind setting this value, only that it must be small enough not to change the operating point but sufficiently excite the system dynamics. Let's choose around 10% of what the nominal controller output is at a steady state.

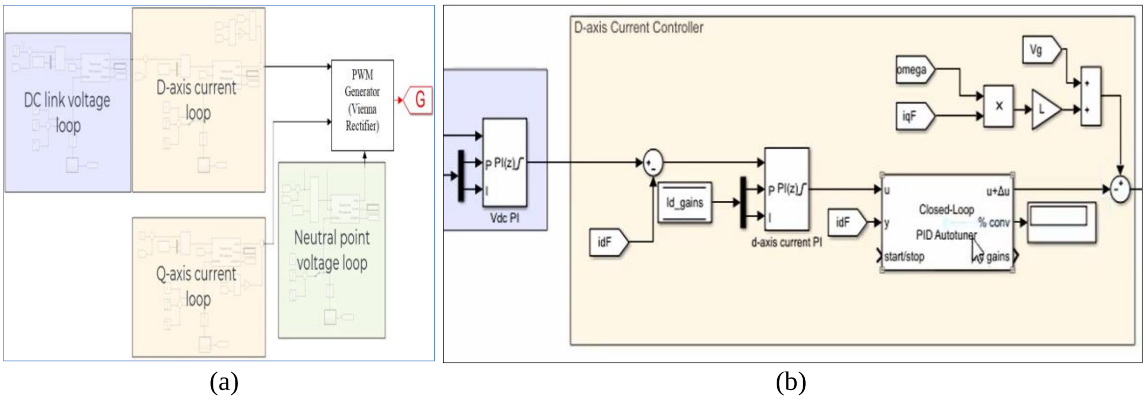


Figure 3. MATLAB-based simulation diagram of; (a) the feedback compensators subsystem; and (b) PID auto-tuner of D-axis current control loop

3. RESULTS AND DISCUSSION

The performance of the dc-link voltage, neutral point voltage controllers, grid voltage and current with different loads is shown in Figure 4. It is observed that with a balanced load across the buses, a slow rise time. When individual loads are introduced later on the neutral point voltage controller does not perform as expected causing an imbalance of the DC-link capacitor voltages, and therefore causing link voltage to diverge from the reference as clearly shown in Figure 5.

To improve these responses by tuning the controller loops, let's set up the controller loops with the closed-loop PID autotuner as described in methodology diagram. The overall simulation diagram before and after adding the PID Autotuner is shown in Figure 6. We added autotuner blocks at the closed-loop PID controllers for the other loops and set the tuning requirements. For the Q-axis controller, the closed-loop PID autotuner block has been set up for bandwidth and phase margin of 3000 rad/s and 60 degrees respectively and the sine amplitude to 0.19.

The DC-link voltage loop will run almost 10 times slower than the current loops so the bandwidth has been set to 400 rad/s. The phase margin is set to 60 degrees and the sinusoidal perturbation amplitude to 1. Finally, the neutral point voltage controller has the bandwidth, phase margin, and amplitude of perturbations set to 20000, 60, and 0.01 respectively. With these blocks placed in each of the four controller loops, the experiment starts/stop times for these loops are set using these step blocks.

The experiments have been conducted after the system has reached a steady-state first for the inner current loops, followed by the outer DC-link voltage loop and then the neutral point voltage loop. From prior simulations, the system reaches a steady state at around 0.6 seconds. So, we conducted the experiments sequentially after this point in time, first for the inner D axis current controller from 0.66 to 0.76 seconds using the step commands.

A conservative estimate for setting the experiment time duration was 200 over the set bandwidth. Similarly, we followed it by tuning the Q-axis current controller after letting the transients settle and running the experiment from 0.8 to 0.9 seconds. Likewise, we followed this for the DC-link voltage controller from 0.95 to 1.45 seconds, and the neutral point voltage controller from 1.7 to 1.72 seconds. With this setup, we executed the simulation. The experiments were conducted and the closed-loop PID autotuner blocks tuned and updated the gains.

All the four controllers are tuned independently in the system because the closed-loop autotuner PID controller can only tune a single PID block at a time. As a result, we start by tuning the inner current controllers, then the voltage neutral controller, and the DC-link voltage controller. During the simulation of the model: The voltage neutral controller (1.7 to 1.72) seconds, the D-axis current controller (0.66 to 0.76) seconds, the Q-axis current controller (0.8 to 0.9) seconds, the DC-link voltage controller (0.95 to 1.45 seconds), and the voltage neutral controller (0.95 to 1.45 seconds). Once each controller has been tweaked, the data store memory element is used to update the controller gains. With the same load changes (see Figure 7), the performance of the controller with the initial gains in blue and the new gains in pink for the main DC link voltage is shown in Figure 8(a), and for the DC-link capacitor voltages is shown in Figure 8(b).

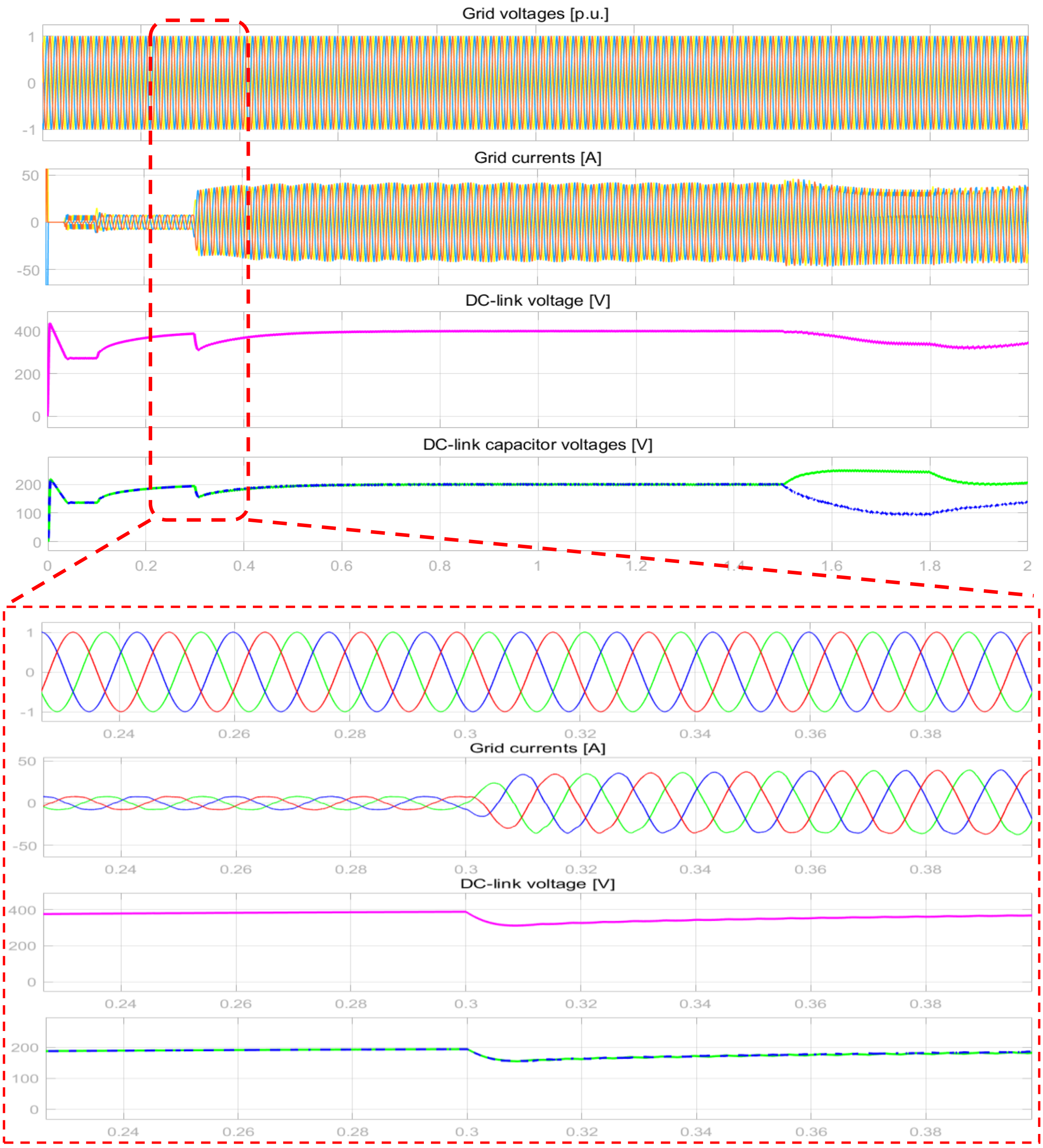


Figure 4. DC-link voltage, neutral point voltage controllers, grid voltage and current with different loads.

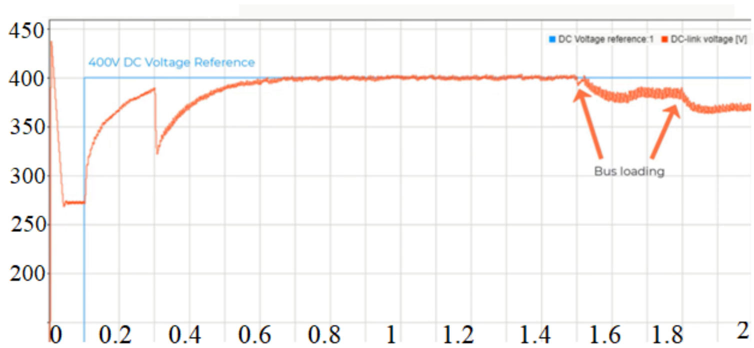


Figure 5. DC-link voltage that diverges from the reference due to imbalance loads.

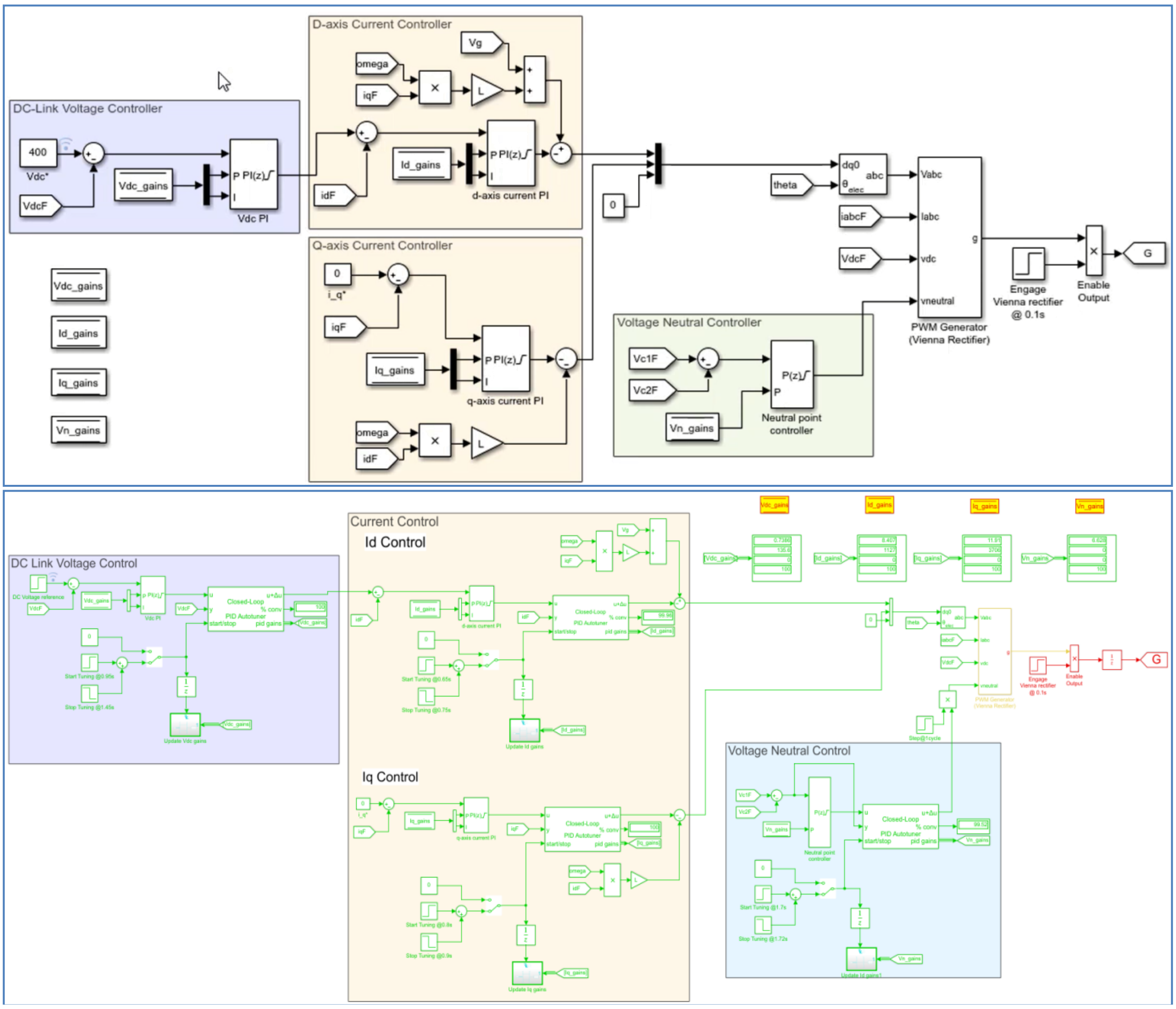


Figure 6. Simulation diagram before and after adding the PID autotuner

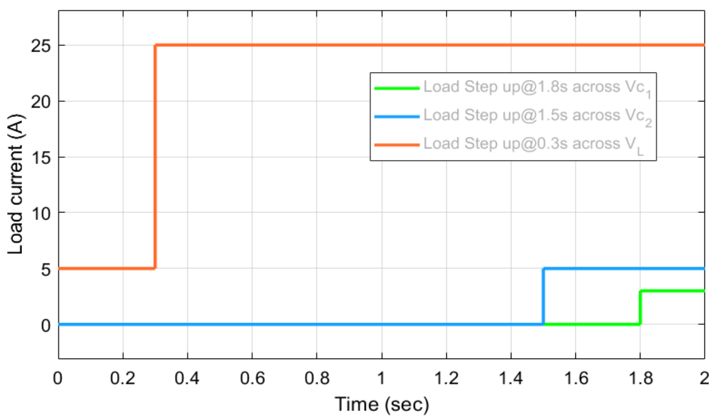
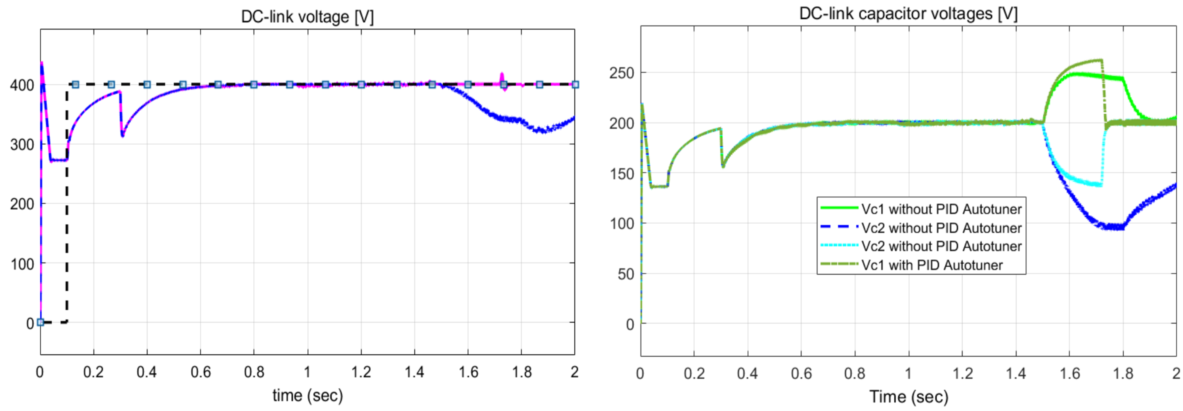


Figure 7. The loads timing change

The response time has improved considerably here when the balanced load is introduced. After the time 1.5 sec, the simulation with the individual loads being introduced the neutral point voltage controller did a good job of keeping the voltage neutral point stable compared to the older controller gains. The performance, after adding the PID auto-tuner, of the dc-link voltage, neutral point voltage controllers, grid voltage and current with different loads is shown in Figure 9.



(a) (b)

Figure 8. The performance of the controller (a) for the main DC link voltage and (b) DC-link capacitor voltages

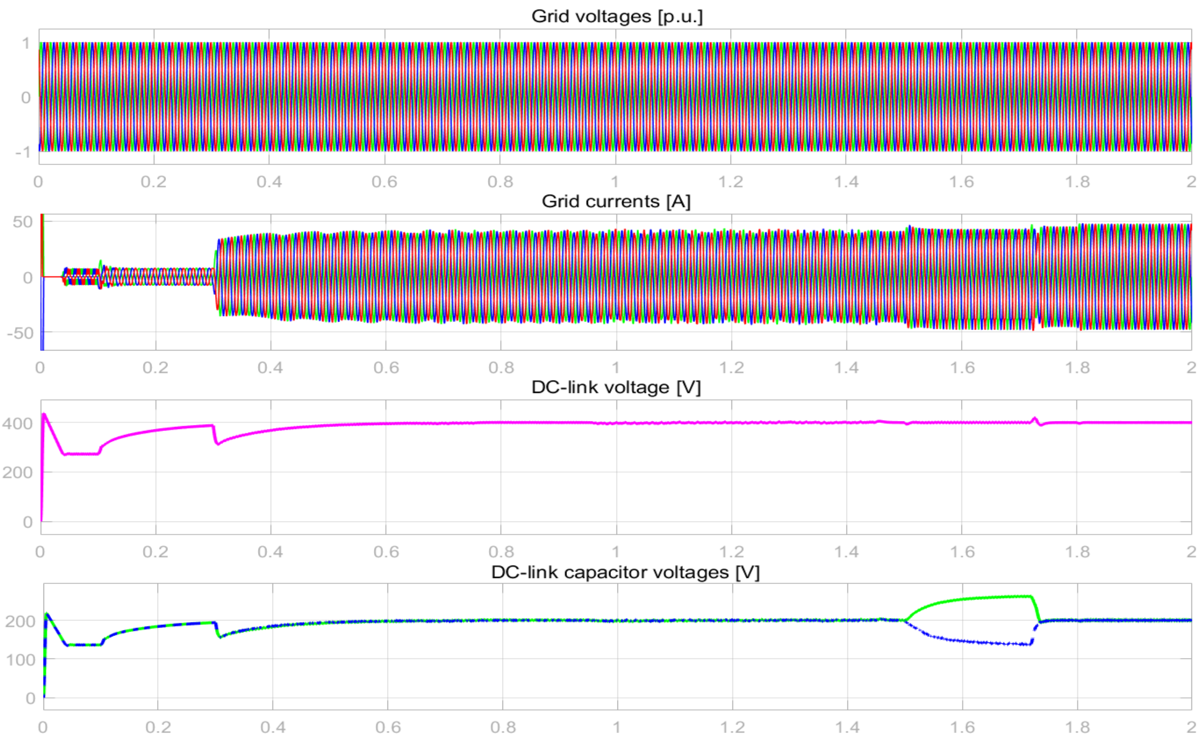


Figure 9. The performance, after adding the PID auto-tuner, of the dc-link voltage, neutral point voltage controllers, grid voltage, and current with different loads

4. CONCLUSION

It is possible to adjust a single PID controller every time using the closed-loop aut-otuner PID controller. During a closed loop experiment, it inserts sinusoidal perturbation waveforms at the input of the plant to measure the subsequent output of the plant. The Auto-tuner calculates PID gain values according to frequency response of plant that measured at a little number of locations close to the preferred bandwidth when the experiment ends. The advantages of this strategy are that; 1) if an unanticipated disruption occurs during the experiment; the existing controller rejects it to ensure safe operation; 2) by ignoring disturbance signals, the present controller keeps the plant functioning close to its normal operating point. When using the PID autotuner in closed-loop simulations and real-time applications, the following steps need to be kept in mind; i) either the plant must be asymptotically stable, which means that all poles must be rigorously stable, or it must integrate; ii) an unstable plant will not work with the autotuner closed-loop PID controller; iii) the presenting closed-loop controller must be stable; iv) to approximate the frequency responses of the plant further precisely in actual time, it is necessary to limit the incidence of every interruption in the Vienna rectifier circuit throughout the experiments; v) the auto-tuner closed-loop PID controller assumes that the plant output is solely a response to the perturbation signals injected.

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