

Dynamic response investigation of PV based CLCIS fed IMD applications using HC and SMC

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ABSTRACT

This paper explains a solar photovoltaic (SPV) based cascaded landsman converter inverter structure (CLCIS) which feeds induction motor drive (IMD) using hysteresis controller (HC) and sliding mode controller (SMC). The aim is to create SPV based cascaded landsman converter (CLC) with an enhanced dynamic response. HC and SMC enabled systems are designed and created using MATLAB. The standards of procedure and simulation results are examined. The simulation results of HC and SMC enabled systems are analyzed concerning time-domain parameters and a comparison has been exhibited. The proposed SMC ensures a model reference robust dynamics against changing voltage conditions of photovoltaic (PV) based CLCIS fed IMD system. The consequences reveal that the dynamic response with SMC is better compared to the HC enabled CLCIS-IMD system.

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1. INTRODUCTION

Besides the worldwide energy crisis, the sustainable development of electrical energy from various natural resources has remained a challenge for many countries. It has become the focus of the national policies and strategies of many nations. Additionally, the power from sustainable energy sources has become an encouraging choice for productive appliances. Hence, the solar photovoltaic (SPV) cluster wipes out every one of these worries and makes a regular fountain of electrical energy. As no ozone harming substances outflow, no fuel and support expenditure, no water utilization strategy states that SPV cluster framework furnishes perfect, and efficient energy with continuous supply all the day at whatever point sun-based irradiance is accessible. Photovoltaic (PV) cells are made up of silicon which was presented in the 1980's and got disregarded in 1990's. At that point, increasingly further examination was carried out about PV cells. Greater speculation was approaching, the expense of PV cells got diminished. However, the productivity was as low as 5-6% and the underlying expense was elevated. At present, the effectiveness of SPV is 15-16% for shopper sun-powered board, 27% for the business sun-powered board. A few gatherings are taking an attempt at SPV framework and guarantee 44.7% productivity of sun-oriented board which is a great sign for the industry. Despite all these advancements, even now there are few difficulties, for example, cost, proficiency, irregularity, and so forth. At present SPV cluster, working zone got expanded step by step and is utilized in low, medium and high-power applications like street lighting, home appliances, water siphoning in the amid-area, irrigation in forest areas, animal husbandry, and industries which are situated in isolated areas. This SPV is more utilized for water pumping where persistent water supply is requisite for both day and night mainly in areas where the grid power is not sufficient. For these applications, the SPV is used along with a

single phase or three phase induction motor (IM). Due to its ease, ruggedness and low maintenance, IM is utilized in all aspects of the home and modern utilities.

Nonconventional energy sources are becoming an option just because of diminishing petroleum derivatives. Utilizing sun-based energy as a regular source of energy will give additional hope [1]. To streamline the working purpose of the SPV cluster to get the greatest conceivable power yield by the procedure of the predominant extreme power point tracing. The converter goes about as an intermediary between the SPV cluster and voltage source inverter (VSI) sustaining the brush less direct current motor (BLDCM) in [2]. Fuzzy logic can be regarded as a numerical theory implemented to achieve the best operating point of the converter by appropriate modeling, controlling of PV based pumping system and BLDCM [3]. The design and implementation of solar PV based converter fed BLDCM speed control applied in water pumping systems were adequately discussed in [4]–[6]. Canonical switching cell converter (CSC) is used as a middle converter between solar PV panel and inverter to harness maximum power to drive permanent magnet BLDCM drive applied in water propelling system [7]. Modified landsman converter (LC) in bridgeless arrangement is realized to optimize the output power of PV array using various control strategies [8]–[10].

Identification of the best topology DC-DC converter available for PV based water pump applications was done by Chandrasekhar *et al.* [11]. Performance comparison of three non-isolated advanced converters namely, Landsman, Leo, and Zeta indicate that the LC is the best option for a solar water pumping system. Three phase IM invites complicated control and heating issues if the voltage levels are low [11]. The induction motor drive reliably achieves the expected speed to draw off the water independent of the environmental variations. Enhanced time response of PV based cascaded landsman converter inverter structure (CLCIS) enabled by fractional-order proportional-integral-derivative (FOPID) controller was presented [12]. Further comparison of FOPID controller with proportionate resonant (PR) controller on time-domain of LC was done [13]. A modified and advanced LC that plays the main role in renewable energy sources was proposed by Maroti *et al.* [14]. The recommended structure promises a high voltage transformation ratio.

In a real-world scenario, the problem of voltage sag and swell is fixed by effective control of dynamic voltage restorer (DVR). Apart from the discussion on conventional methods to control DVR which fixes the issue, hysteresis band voltage control was proposed. Hysteresis controller (HC) results in improved control of load voltage and decides the sequence, timing of switching signals for inverter operation [15]. Premila and Kumar [16] proposed boost-re-boost converter-inverter assembly in cascading manner controlled by proportional resonant (PR) and hysteresis controllers to attain maximum gain and compared the dynamic performances. Hysteresis control of buck converter with line current feedback to control voltage output of capacitor was recommended by Dai *et al.* [17]. Hysteresis bandwidth is the guideline to control the capacitor voltage. A grid linked PV system with irregular load was proposed by Prasad *et al.* Here HC was suggested for the interface between PV source and grid. This system provides the option of giving power to the grid and extracting power from the grid in case of excessive and shortage of power from PV sources [18]. Integral sliding mode controller (ISMC) was implemented in buck converters, to alleviate the inconsistent switching frequency (ISF) issue confronted during unpredictable load conditions and source voltage fluctuations. ISF invites complicated filter design [19]. Second-order sliding SMC design and algorithm were recommended by Ding *et al.* [20]. PI enabled SMC for DC-DC buck converter was proposed for the application of precise power supply. Adaptive tuning technique was implemented for better load regulation [21]. The strategy of SMC with PI sliding surface for regulation and tracing of unreliable process control systems was implemented [22], [23].

Xu *et al.* suggested a sliding mode control system for the switched reluctance motor (SRM) to mitigate interference in SRM. A SMC was developed for an evolving planar switched reluctance motor (PSRM) that would allow exact position control and be capable of mitigating magnetic interferences. The physical structure and mathematical model of the SMC with familiar parameters obtained by recursive least-squares algorithms were given sequentially. Then, a switching function and a reaching law of the SMC were determined. The control law for the SMC is derived from this. Additionally, the permanence of the SMC was proved using the Lyapunov stability theorem [24]. The nonlinearity of conventional converters laid a pathway to design dynamic control methods which lead to stable system performance irrespective of system uncertainties. Adaptive SMC for higher-order single-ended primary-inductor converter (SEPIC) converter was recommended in this work [25].

The above works do not cite the improvement of transient response using HC and SMC controllers. This research evaluates the performance of both controllers and compares the findings. As of now, an SMC controller is proposed. The objective of this effort is to attain optimized dynamic and steady state response of LC in the time domain. This results in better voltage regulation and voltage gain. Cascaded structure of LC results in improved voltage gain. The proposed work finds application in the areas of renewable energy

resources, soft starting of drive systems, power quality applications, transmission, hybrid/electric vehicle system, and irrigation water pumping systems.

2. DESIGN OF LANDSMAN CONVERTER

A CSC is composed of the combination of switch SW1, capacitor C2, and diode D3. This combination is called a CSC. A CSC combined with an inductor L2 and DC link capacitor C4 is known as a power factor pre-regulator. The LC fed VSI which further energizes the IM along with the centrifugal pump. Figure 1 shows the block diagram of PV based CLCIS fed IM using HC/SMC. The yield of the PV source is boosted using an LC and is given to a pulse-width modulation (PWM) inverter. The design and working modes of LC were adequately discussed in [12], [13]. The actual LC output voltage is compared with the reference voltage and the switching sequence of the converter is decided by controller error.

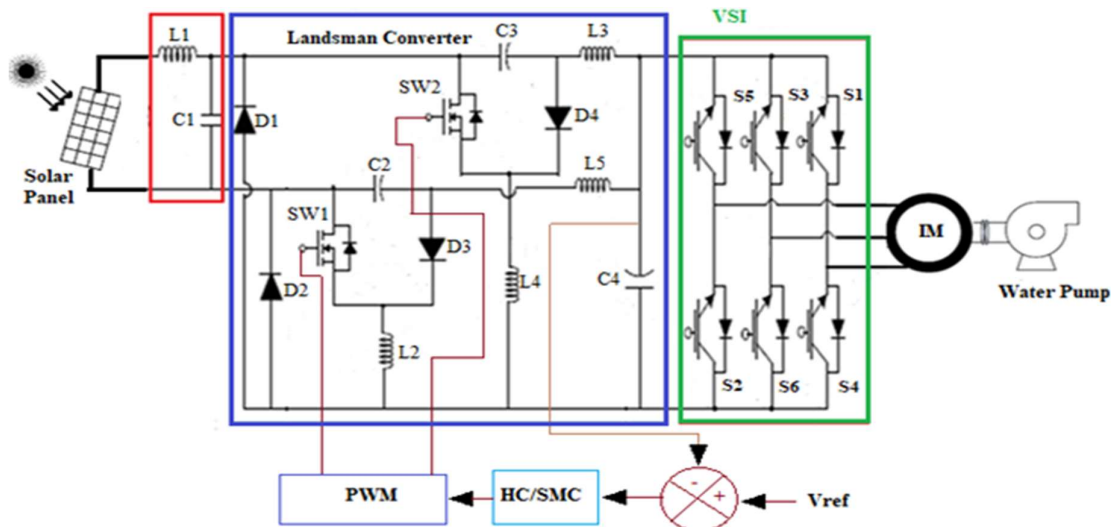


Figure 1. A circuit diagram of PV based CLCIS fed IM using HC/SMC

3. HC ENABLED EXISTING SYSTEM

The HC is known for its easy implementation and rapid dynamic response. This controller is used to regulate LC output voltage and decide switching signals for converter switches. The yield of PV is boosted by the LC. Then VSI converts DC into alternating current (AC). The block diagram of HC enabled CLCIS fed IMD is delineated in Figure 2. The DC output from the PV system is applied to a three-phase inverter through a LC network. The yield of three phase inverter is given to three phase IM.

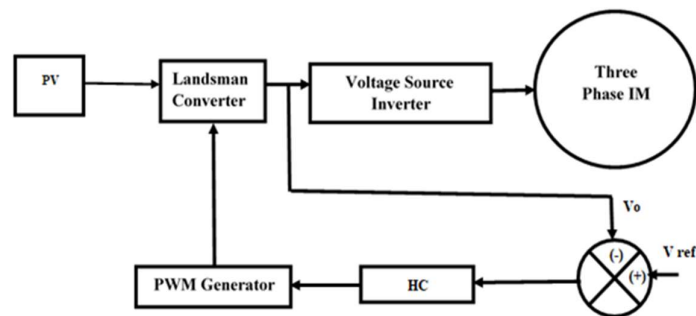


Figure 2. A simplified block diagram of PV based CLCIS fed IM using HC

The design of the system is complex due to the uncertainty of the output. The HC can be made with either a current or a voltage loop. When it is implemented with the current loop, the higher, and lower limit current of the hysteresis controller is calculated as:

$$I_u = I + r/2 \quad (1)$$

$$I_l = I - r/2 \quad (2)$$

where: I_u is upper limit current

I_l is lower limit current

r is the ripple current

$$\text{The value of } r \text{ is given by } r = I_u - I_l \quad (3)$$

In this method, the upper and lower hysteresis band limits are outlined. In the open-loop control approach, a typical problem is to attain the steady output as the LC input voltage changes. But the stable output is attained by a closed-loop scheme. Close-loop scheme is implemented by using a PI controller to generate gate pulses at changing input voltages. Power switching devices need to be controlled when upper and lower limits of hysteresis bands are surpassed in this method, the solid-state switches are not ON if there is no error. Ziegler-Nichols process is used for tuning PI controller.

Hysteresis control is a nonlinear method of voltage or current control. It is also known as two level hysteresis control. This technique employs the comparison between the line voltage and band limit to regulate the output. There are upper and lower bands enclosing the reference voltage. If the error involving the reference signal and measured signal (LC output) reaches maximum or minimum limit, the LC output is enforced to decrease or increase by appropriate switching. The schematic waveform of hysteresis voltage control is shown in Figure 3.

Fixed hysteresis band (H_f) is suggested for open-loop whereas variable hysteresis band (H_v) is recommended for closed-loop to get ripple error at output. The hysteresis band should be small. The switching losses are high due to high switching frequency. HC is employed to generate switching signals to control LC switches to infuse the desired voltage into the system. The circuit diagram of PV-based closed-loop HC enabled LC with IM drive is exposed in Figure 4. The boosted CLC output voltage is fed to the VSI.

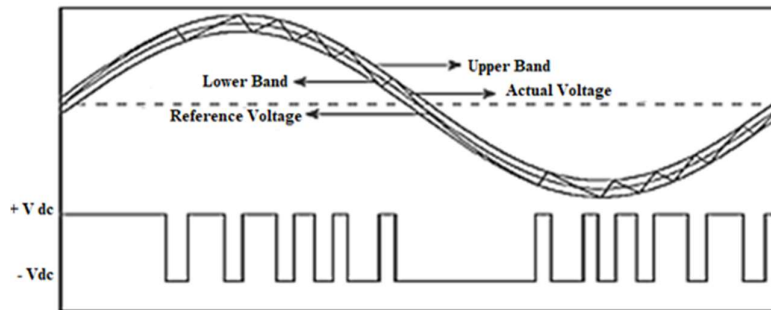


Figure 3. Schematic waveform of hysteresis voltage control

The output of PV panel is 220 V and shown in Figure 5. The HC regulated output voltage of LC is depicted in Figure 6 and its output is 420 V. The tap position indicator (TPI) output voltage which feeds the IM is revealed in Figure 7. The value of controlled output voltage is 415 V. The IM speed response waveform is exposed in Figure 8 and the motor speed is 1300 rpm. The torque of the motor is portrayed in Figure 9.

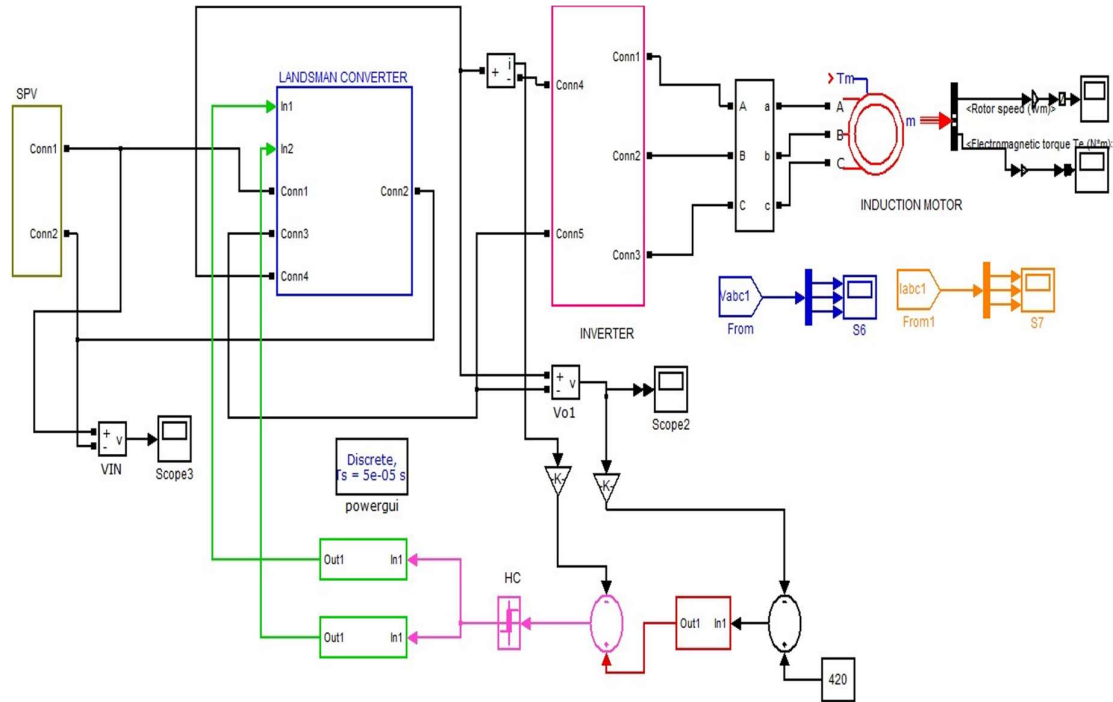


Figure 4. Simulink block diagram of PV based CLCIS with IM using HC

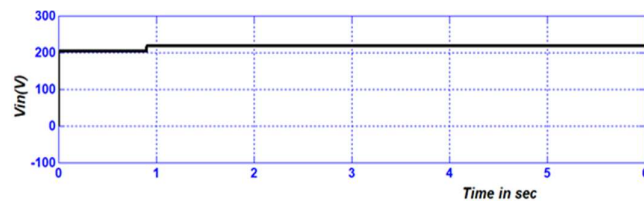


Figure 5. Simulated voltage across solar panel

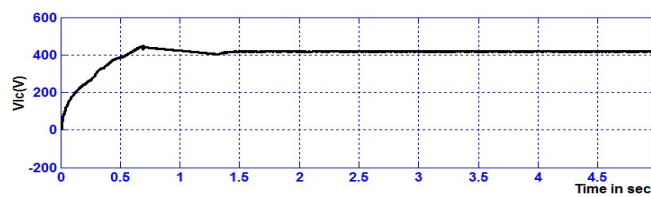


Figure 6. System simulated voltage across LC

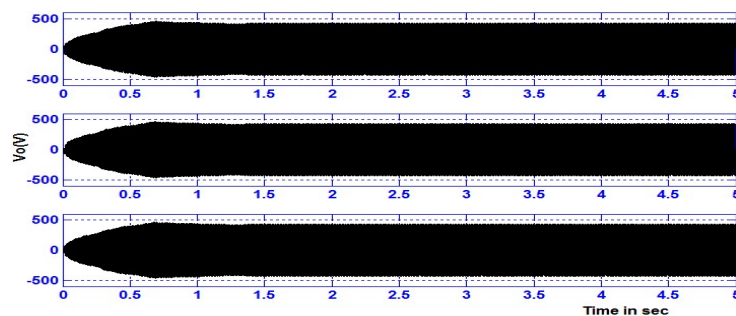


Figure 7. System simulated output voltage across three phase inverter

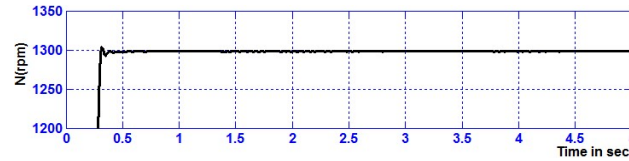


Figure 8. System simulated motor speed

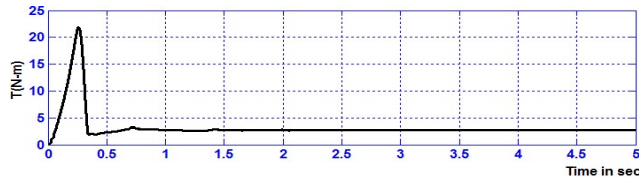


Figure 9. System simulated motor torque

4. SLIDING MODE CONTROLLER ENABLED PROPOSED SYSTEM

The key advantage of an SMC is its reluctance to constraint deviations and external source and load disturbance when on the switching surface. SMC attracts the consideration of researchers due to its robustness and fast dynamic response though it undergoes the problem of chattering. Based on the SM theory, each state variables (SV) are sensed and the equivalent errors were calculated. The sliding function is designed by multiplying errors with suitable gains K_i and adding all the elements. Now SMC maintains this function value close to zero.

Practically, SMC design is done by suitable selection of sliding surface coefficient K_i to ensure reliability in all operating situations. Therefore, an SM technique is recommended for proportional load sharing and steadiness of DC smart grids. The flow diagram of SMC appears in Figure 10.

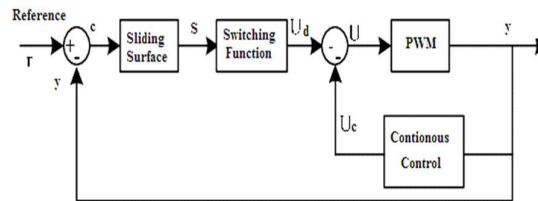


Figure 10. A simplified block diagram of SMC

A linear, time varying system is:

$$\dot{x}(t)=A(t)x(t)+B(t)u(t) \quad (4)$$

It is assumed that a suitable linear SM is defined in 'n' dimensional state space by:

$$S(x)=p_1x_1+p_2x_2+\dots\dots\dots p_nx_n \quad (5)$$

Condition for sliding is indicated as:

$$s\dot{s} < 0 \quad (6)$$

$$u=-K_ix \quad (7)$$

To assure $s\dot{s} < 0$, the below mentioned continuous control law is used.

$$K_i=\alpha_i+\delta_i \sigma_i(x) \quad \delta_i > 0 \quad i=1, 2, 3, 4,\dots\dots n \quad (8)$$

Where δ_i —sliding margin. The above procedure can be implemented to nonlinear systems as exemplified is being as:

$$\dot{x}(t) = f(x(t), t) + g(x(t), t)u(t) \quad (9)$$

Continuing as above, it can be obtained as:

$$u = -\dot{\sigma}(x) - \delta \sigma(x) \text{ where } \delta > 0 \quad (10)$$

In (7), (8), and 10 describe the continuous SMCs for linear and non-linear systems, respectively. The system state to change from a random initial state to the sliding mode and then travel along the designed path. Moreover, error processing is done by the controllers. The time-derivatives and integration of errors are used to stabilize the system. In this case, the sliding surface is represented as a second order differential equation for which numerical study is obligatory to ensure system stability. In addition, the steady state error and settling time are enhanced by additional surface which consists of the combination of voltage-error and capacitor current.

The yield of PV is boosted by the LC and then DC voltage is converted into AC voltage using VSI. Block-diagram of SMC enabled CLCIS fed IM is delineated in Figure 11. The DC output from the PV system is applied to three phase inverter through an LC network. The yield of three phase inverter is applied to three phase IM.

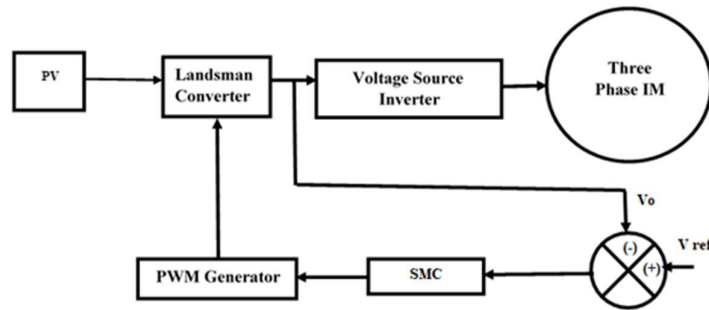


Figure 11. A simplified block diagram of CLCIS fed IM Drive enabled by SMC

A Simulink circuit diagram of closed-loop control of CLCIS fed IMD using SMC is displayed in Figure 12. The boosted CLC output voltage is connected to the VSI system. The actual output voltage and the reference voltage of CLC is compared to compute error voltage or current. Voltage from PV panel to the LC is presented in Figure 13. The output voltage of LC is 420 V and is shown in Figure 14.

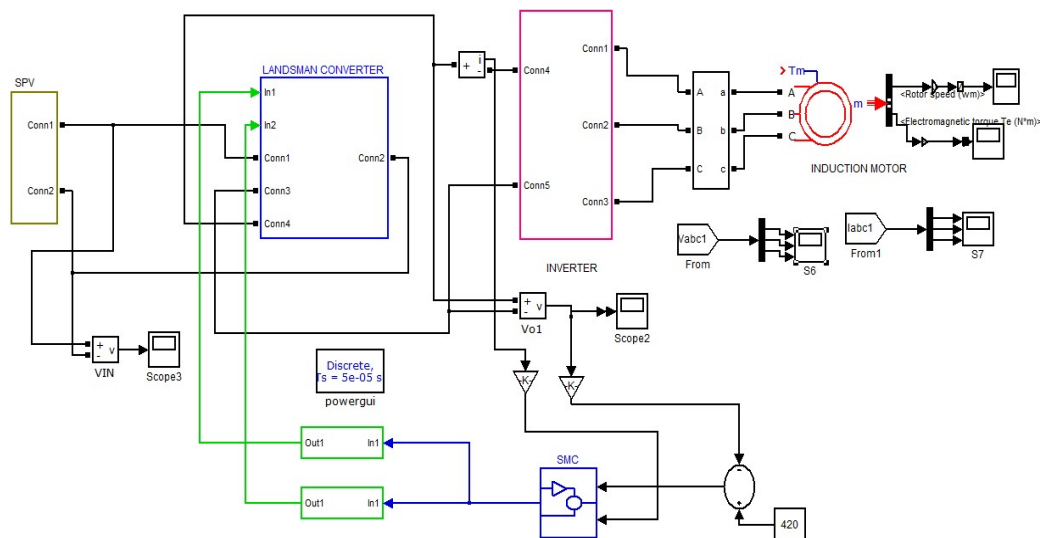


Figure 12. Simulink circuit diagram of PV based CLCIS fed IM using SMC

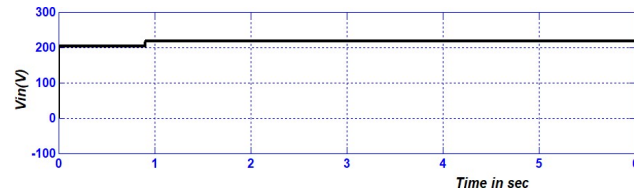


Figure 13. Voltage across PV panel

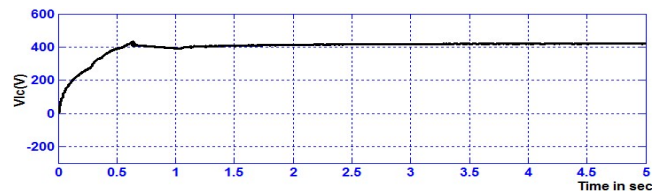


Figure 14. Voltage across landsman converter

The SMC enabled output voltage across the IM is revealed in Figure 15. The value of controlled output voltage is 415 V. The IM speed response waveform is shown in Figure 16 and the value of the motor speed is 1300 rpm. Motor torque is exposed in Figure 17.

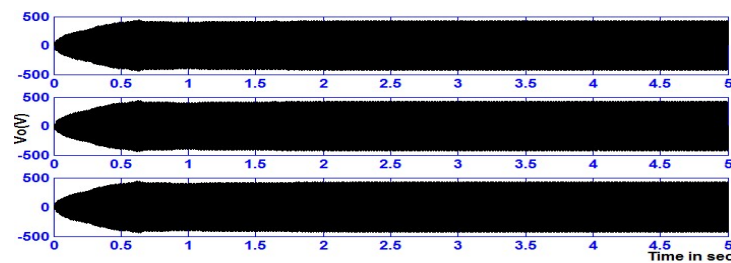


Figure 15. System simulated voltage across three phase inverter

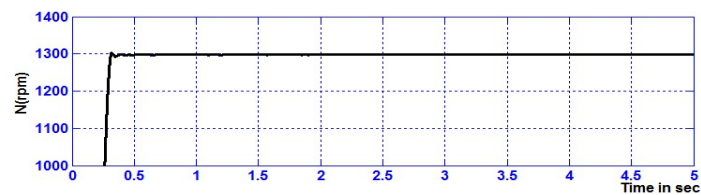


Figure 16. System simulated motor speed

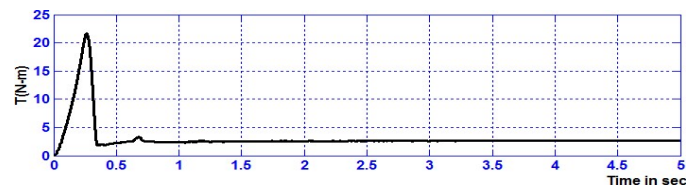


Figure 17. System simulated motor torque

5. RESULTS AND DISCUSSION

Open-loop, HC, and SMC enabled closed loop voltage across the LC are shown in Figure 18. The open-loop voltage across the landsman converter is not settled till 470 V. HC and SMC enabled closed loop voltage across the LC is settled rapidly and its value is 420 V.

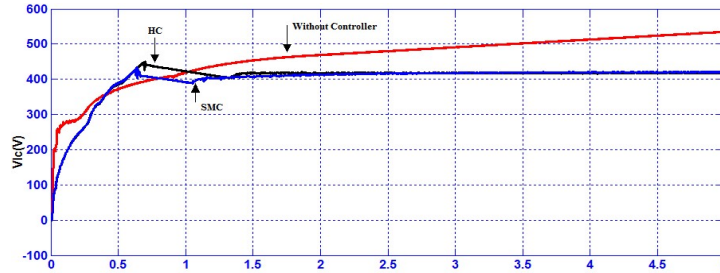


Figure 18. Comparison of voltages across LC in open and closed loop modes

The numerical value of LC regulated output is 420 V and settles effortlessly in closed loop mode whereas, without a controller, it shoots up to 470 V and does not settling easily as it is evident from Table 1. A data comparison of dynamic response parameters with Hysteresis and SM controllers is given in Table 2 and SMC results in diminished rise time (T_r); settling-time (T_s); peak time (T_p); and steady-state error (E_{ss}).

Table 1. Comparison of voltage regulation of LC

Landsman converter	Voltage regulation (Vr)
Without controller	470 V
With controller	420 V

Table 2. Comparison of dynamic performance parameters with HC and SMC

Controller	$T_r(\text{sec})$	$T_s(\text{sec})$	$T_p(\text{sec})$	$E_{ss}(\text{V})$
HC	0.66	1.38	0.70	0.95
SMC	0.62	1.19	0.64	0.76

Figure 19 portrays the dynamic performance parameters comparison in line chart form. X axis represents dynamic performance parameters and Y axis stands for time in seconds.

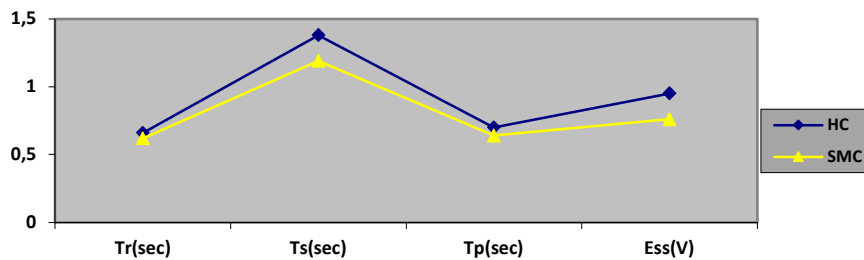


Figure 19. Line chart for dynamic response parameter of HC and SMC

6. CONCLUSION




A closed-loop assessment of LC was conducted using HC and SMC. The LC helps in the removal of additional filtering requirements. A smooth DC voltage is obtained which is boosted by the cascaded structure in the LC. The SMC regulates the voltage at its earliest, thus providing constant output voltage and speed. Further investigation and MATLAB simulation show that the SMC-powered model settles faster with reduced steady-state error. The benefits of the suggested system are higher voltage gain and better speed response. The SMC powered model exhibits superior steady-state and transient response than its HC counterpart. When solar irradiance is not available, continuous operation is not possible. To make this system sustainable, energy storage elements, and wind energy system can be interfaced with appropriate control module to make the output reliable most of the time. Fuzzy logic controller maybe employed to enrich the present work.

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