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SOLAR WATER PUMPING SYSTEM EMPLOYING PMSM DRIVE BASED ON TYPE-2 FUZZY CONTROLLER

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Abstract: The main aim of this project is Solar-PV water pumping system employing PMSM drive based on Type-2 FLC control strategy. This paper proposes the design and investigation of Type-2 fuzzy recompensated hybrid proportional integral (PI) controller for Permanent Magnet Synchronous Motor (PMSM) driven standalone solar water pumping system. Conventional proportional integral (PI) controller usually has fixed gains, which makes them quite sensitive to the parameter variations. In order to improve its performance, both during dynamic and steady state conditions, the presented controller introduces a Type-2 fuzzy controller, which processes the speed error. The speed along with the processed output is inputted to the PI controller for speed control of PMSM. This topology uses a Solar Photovoltaic (PV) array to convert the solar power into electrical power. The energy obtained is utilized to rotate the PMSM using a 3-ϕ Voltage Source Inverter. The PMSM is coupled to a pump, which performs the water pumping. An intermediate stage DC – DC converter is utilized to maximize the power output using an incremental conductance algorithm. A PV feed-forward term is incorporated to provide an accelerated performance. This topology is modelled and its response is manifested through simulation studies using MATLAB/Simulink under different atmospheric conditions.

Keywords: Photovoltaic (PV), DC – DC converter, 3-ϕ Voltage Source Inverter, Permanent Magnet Synchronous Motor (PMSM), Type-2 fuzzy controller

I.INTRODUCTION

In an era of growing power demand and declining conventional energy sources, renewable energy (RE) sources offer encouraging solutions for full-filling the rapidly increasing gap between energy need and supply. Moreover, the RE sources also provide feasible solution for increasing global warming by minimizing the carbon footprint. An increased use of RE sources, would lead the world towards a sustainable development. Various government authorities, researchers and electric power utilities are working towards greater use of RE sources. Among numerous RE sources, the solar energy is one of the best forms of energy that can be easily harnessed. There are several ways for utilizing solar energy. Nowadays reducing installation cost of solar photovoltaic (PV) generation system, has significantly increased its popularity and encouraged its utilization for numerous applications [1-2]. Solar water pumping has emerged as one of the potential applications of solar PV generation system [3]. It is highly advantageous for remote areas receiving descent insolation and having no grid connectivity. It would help in the improving the living standard by fulfilling the basic water demand in day-to-day life. Moreover, it would also encourage agricultural as well as industrial activities in remote areas [4]. Solar water pumping system requires an electric drive for rotating the pump. Various DC and AC drives are being utilized for solar water pumping [5-9]. Solar water pumping system utilizing a DC motor, suffers a grave issue of increased maintenance due to wear and tear of brushes and commutator assembly [5]. Solar water pumping systems using AC motor drives, generally utilize an induction motor for its robustness and low cost [6]. However, lower efficiency and higher reactive power demand, make it relatively inefficient for this application [7]. Lower efficiency demands an increased size of solar PV array. Permanent magnet synchronous motor (PMSM) provides an exceptional solution to these issues [8]. An increased efficiency, increased power density, good power factor and good dynamic performance make PMSM fairly practicable for solar water pumping as compared to other electric drives [8-10]. Vector control and direct torque control (DTC) are the two mainly utilized techniques for speed control of PMSM [11]. DTC offers a simple and fast speed control by distinctly controlling torque and flux. However, it incorporates torque and flux ripple [12]. Vector control provides a better speed response by splitting the stator currents into direct axis and quadrature axis components and controlling them separately as field and armature current, respectively as in case of a DC motor [13]. In order to overcome these issues, non-linear control techniques based on sliding mode control [14], artificial intelligent control [15-16], robust control [17], adaptive control [18], backstepping control [19] and many others have been presented in the existing literature. All the above techniques improve the system performance at varying implementational complexity. However, most of them require system parameters for their proper operation. It has been observed in the existing literature that the artificial intelligent techniques provide an improved dynamic performance for nonlinear systems with reduced dependence on the system parameters. Fuzzy logic control (FLC) is one of the widely accepted intelligent techniques [15]. FLC forms a set of mathematical modelling with decision making based on the linguistic rules formed from the prior experience of the designer. Although in comparison with the conventional PI control, the FLC is computationally exhaustive and requires larger memory size processor for its implementation. However, with recent advances in the processor technology, it no more remains a major limitation. To maximize the power extraction from a solar PV array, solar PV integrated system requires maximum power point tracking (MPPT). Numerous MPPT techniques are already presented in the past. Fractional open circuit voltage and fractional short circuit current are the simplest MPPT techniques. However, they offer lower tracking efficiency. The incremental conductance (INC) and perturb and observe (P&O) methods are two frequently utilized MPPT techniques with excellent tracking efficiency. Many other methods based on optimization technique such as neural network, genetic algorithm, fuzzy logic, Grey Wolf optimization, particle swarm optimization, etc. have also been presented, which possess excellent tracking efficiency even at the time of partial shading [20]. Among the two frequently utilized algorithms, P&O is easily implementable. However, it has a drift and steady state oscillation problem. Although the INC method of MPPT even after being a bit complex, provides an excellent performance during steady state and rapidly changing environmental conditions. This work presents a solar PV array powered PMSM driven solar water pumping system. The presented topology utilizes a hybrid PI controller for speed control of PMSM and an INC based MPP tracking for optimum power extraction from solar PV array. The hybrid PI controller is a combination of FLC and PI controller. The proposed Type-2 FLC modifies the speed error in accordance to its magnitude and direction. The modified error along with the speed error is inputted to the PI controller and thereby the speed of the PMSM is controlled. The presented controller improves the dynamic as well as steady state response of the solar water pumping system. The complete system along with the presented controller, is modelled and simulated using MATLAB/Simulink Simscape Sim power system toolbox.

II. PROPOSED SYSTEM

The below figure shows the proposed system configuration for solar water pumping system. The presented system includes of a solar PV array, a DC – DC boost converter, a 3- phase insulated gate bipolar transistor (IGBT) based voltage source inverter (VSI), a PMSM and a pump. The solar PV array converts the energy from the sunlight into electrical energy. This electrical energy is inputted to a DC – DC boost converter. The boost converter adjusts the solar PV array voltage by adjusting the duty ratio in such a way that the solar PV array voltage is regulated at its MPP voltage. The output power of the boost converter, is inputted to the VSI. The VSI processes this power and drives the PMSM. The PMSM converts the electrical energy into mechanical rotational energy, which is utilized to rotate the pump mechanically coupled to the PMSM. As the pump rotates, the water pumping operation is realized. The design of presented topology, involves proper sizing of the solar PV array, a DC – DC boost converter and the pump in such a way that pumping operation can be performed even at lower insolation levels. The design of various system components, is presented in following subsections.

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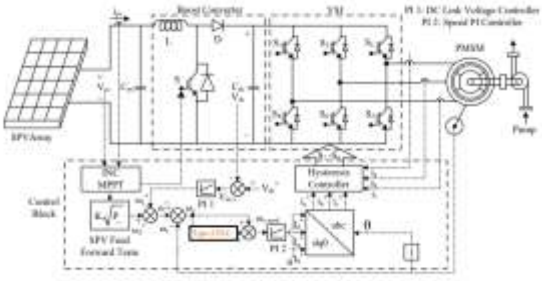

Fig.1. Proposed configuration for solar water pumping system.

III. CONTROL STARTAGRY

The control of the topology presented in Fig. 6.1, is basically divided into three major parts. The first part discuses about the MPPT operation, second part discusses about the generation of reference speed and modified speed error whereas third part discusses about the speed control of PMSM.

A) MPPT

In this topology, MPPT is attained by utilizing an INC method. An INC MPPT algorithm regulates the operating point at a value where instantaneous conductance is equal to incremental conductance. It provides a fast MPP tracking even under rapidly changing environmental conditions. The advantages of theoretically no steady state oscillation and fast dynamic response, make it quite effective for solar water pumping. Fig. 6.2 depicts the algorithm for INC MPPT method. For a good steady state and dynamic performance, a proper value of step size needs to be selected. The step size chosen for this work is 0.01. Various governing equations involved in InC based MPPT technique that use PV array current (Ipv) and voltage (Vpv) as inputs, are expressed as,

$$\Delta I_{pv} = I_{pv}(k) - I_{pv}(k-1)$$

1

$$\Delta V_{pv} = V_{pv}(k) - V_{pv}(k-1)$$

2

$$\frac{\Delta I_{pv}}{\Delta V_{pv}} = \frac{-I_{pv}}{V_{pv}}, \text{ at MPP}$$

3

$$\frac{\Delta I_{pv}}{\Delta V_{pv}} > \frac{-I_{pv}}{V_{pv}}, \text{ at Left of MPP on } P_{pv} - V_{pv} \text{ curve}$$

4

where, Ppv is the PV array power

$$\frac{\Delta I_{pv}}{\Delta V_{pv}} < \frac{-I_{pv}}{V_{pv}}, \text{ at Right of MPP on } P_{pv} - V_{pv} \text{ curve}$$

5

An INC algorithm adjusts the duty ratio of the boost converter such that (10) is satisfied.

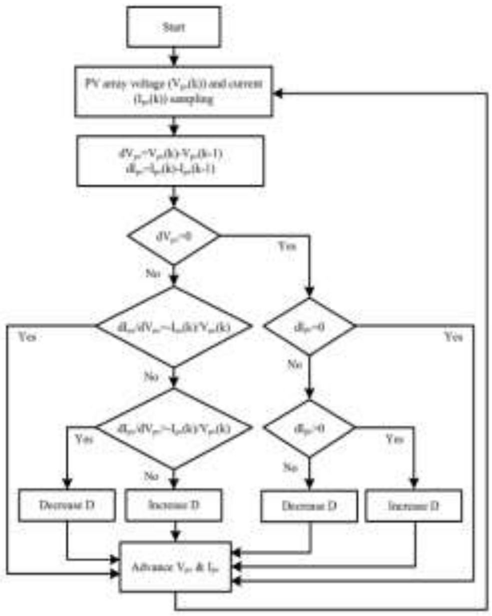

Fig.2. INC MPPT algorithm

B) Generation of Reference Speed and Modified Speed Error

In the presented topology, the reference speed (ω*) is generated in two parts. First part comes from DC link voltage controller whereas second part comes from solar PV power feed-forward term. The ω* is compared to actual speed (ωr) to generate a speed error (ωe). ωe along with change in ωe (Δωe) is inputted to the Type-2 fuzzy logic controller (FLC) to generate another speed error (ωe flc) based on the intelligence of the Type-2 FLC in order to compensate for system non-linearities. Both the errors are summed up to generate modified speed error (ωe mod), which is inputted to the speed controller.

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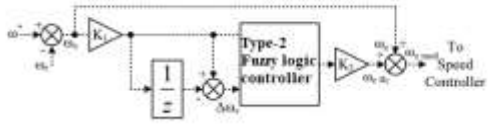

Fig. 3 Schematic diagram of hybrid PI speed controller.

The schematic diagram for the hybrid speed control is presented in Fig. 3. The DC link voltage error at kth sample, is expressed as,

$$V_{dc\,e}(k) = V_{dc}*(k) - V_{dc}(k) \quad 6$$

This voltage error is inputted to DC link voltage controller. The DC link voltage controller minimizes this error by adjusting its output and its output considered as ω1 * (k). ω1 * is expressed as,

$$\omega_1^*(k) = \omega_1^*(k-1) + K_{pd}\{V_{dc\,e}(k) - V_{dc\,e}(k-1)\} + K_{id}V_{dc\,e}(k) \quad 7$$

Where, Kpd and Kid are proportional and integral constants, respectively utilized in DC link voltage controller. ω2 * (k) is generated from PV power feed-forward term such that,

$$\omega_2^*(k) = K_{pv}P_{pv}(k) \quad 8$$

Where, Kpv is solar PV feed forward constant. The reference motor speed ω* is a sum of ω1* and ω2* .

$$\omega^*(k) = \omega_1^*(k) + \omega_2^*(k) \quad 9$$

ω*(k) is compared to ωr (k) and the speed error is as,

$$\omega_e(k) = \omega^*(k) - \omega_r(k) \quad 10$$

The rate of change in speed error is expressed as,

$$\Delta\omega_e(k) = \omega_e(k) - \omega_e(k-1) \quad 11$$

This speed error along with the rate of change in speed error, is inputted to the FLC. The FLC uses ωe (k) and Δωe (k) and gives an output ωflc (k) based on its rules.

$$\omega_{e\,flc}(k) = f\left(\omega_e(k), \Delta\omega_e(k)\right) \quad 12$$

The modified speed error for the PI controller, is expressed as,

$$\omega_{e\,mod}(k) = \omega_e(k) + \omega_{e\,flc}(k) \quad 13$$

Speed Control of PMSM

In this topology, the speed control is attained using vector control. After the generation of ωe mod, it is inputted to the speed controller. The speed controller output is considered as reference quadrature axis current (Iq*). The speed controller minimizes ωe mod to zero by adjusting Iq*. Iq* is expressed as,

$$I_q^*(k) = I_q^*(k-1) + K_{p\omega}\{\omega_{e\,mod}(k) - \omega_{e\,mod}(k-1)\} + K_{i\omega}\omega_{e\,mod}(k) \quad 14$$

Where, Kpω and Kiω are proportional and integral constants, respectively utilized in speed controller. Since for solar water pumping, the pump speed needs to be controlled below base speed, therefore no field weakening is required. Hence, Id* is kept zero. Using an inverse Park’s transform (dq0 to abc), the reference stator currents of PMSM (ia*, ib* and ic*) are evaluated from Id* and Iq*. The sensed motor phase currents ia, ib and ic and the reference currents ia*, ib* and ic* are inputted to the hysteresis controller, which generates gating signals for VSI.

IV. PROPOSED TYPE-2 FUZZY CONTROLLER

When a system has considerably large sureness, Type 1 Fuzzy Logic Controller (T1FLC) are unable to attain the desired level of performance with a rational complexity of the structure. In such cases, the use of Type 2 Fuzzy Logic Controller (T2FLC) is advised as the favorable FLC in the studies in areas, such as forecasting of time-series, controlling of mobile robots, the truck backing-up control problem, Very Large-Scale Integration (VLSI) and Field Programmable Logic Devices (FPGA). Executions of T2FLC reveals that when the parameters are appropriately adjusted, T2FLC can result in a better ability to predict as compared to T1FLC [Liang Q and Mendel J. M (2000)]. For machines like real time mobile robots, T2FLCs are most suitable application. For the case of real time implementation, literature survey shows that a conventional T1FLCs are unable to handle the

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uncertainties in the system efficiently and a T2FLC using type- 2 fuzzy sets results in a better performance. Also, by using T2FLC the quantity of regulations to be determined also reduces although the parameters to be determined do not get reduced.

In the year 1975, Zadeh gave the concept of Type-2 fuzzy sets. These type-2 Fuzzy sets were a mere extension of type-1 fuzzy sets. A Fuzzy Logic Set described using at least one type-2 fuzzy set is called a type-2 FLS.Type-2 FLSs are useful to measure uncertainties. Type-2 fuzzy set help to model and to minimize the effects of uncertainties in rule-based FLS.

The theory of Type-2 fuzzy sets was further evolved by Mendel and Karnik. Type-2 Fuzzy Logic sets seems to be a more favorable method than their type-1 counterparts in cases of handling uncertainties like noise in data and changes in environmental conditions. When the effects of the measurement of noise in type-1 and type-2 FLS were compared, it was concluded that the use of T2FLS in practical applications which reveal measurement noise and modelling uncertaintiesis a better option than type-1 FLS.

Usually, Fuzzy logic is a nonlinear mapping of an input data vector into a scalar output and the primary mechanism for doing this is a list of if-then statements called rules. All rules are evaluated in parallel, and the order of the rules is unimportant. The rules themselves are useful because they refer to variables and the adjectives that describe those variables. Before a system is built that interprets rules, all the terms which are to be used and the adjectives that describe them need to be defined.

ARCHITECTURE OF TYPE-2 FUZZY LOGIC SYSTEMS

Hagras, H. (2007) presented that Type-2 fuzzy sets are finding very wide applicability in rule- based fuzzy logic systems (FLSs) because they let uncertainties be modeled by them whereas such uncertainties cannot be modeled by Type-1 fuzzy sets. A block diagram of a Type-2 Fuzzy Logic System (T2FLS) is described in Figure 4.

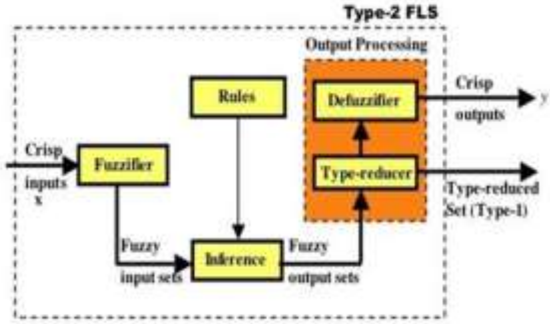

Figure 4: Block diagram of Type-2 Fuzzy Logic System

In the block diagram, there is an extra block - type reducer, which is not present in Type-1 FLS but is needed in Type-2 FLS design. Though the Type 2 FLS has some advantages when dealing with uncertainties, but it also increases the mathematical calculation.

The blocks of Type 2 FLS are as:

Fuzzifier: The fuzzifier maps crisp inputs into Type-2 fuzzy sets which activates the inference engine.

Rule base: The rules in a T2FLS and T1FLS are same, but antecedents and consequents are represented by Type-2 fuzzy sets.

Inference: Inference block assigns fuzzy inputs to fuzzy outputs using the rules in the rule base and the operators such as union and intersection. In type-2 fuzzy sets, join (⊔) and meet operators (⊓), which are new concepts in fuzzy logic theory, are used instead of union and intersection operators. These two new operators are used in secondary membership functions.

Type-reduction: The Type-2 fuzzy outputs of the inference engine are transformed into Type-1 fuzzy sets that are called the type-reduced sets. There are two common methods for the type- reduction operation in the T2FLSs: One is the Karnik-Mendel iteration algorithm, and the other is Wu-Mendel uncertainty bounds method. There are as many type-reduction methods as there are type-1 defuzzification methods. An algorithm developed by Karnik and Mendel now known as the KM Algorithm is used for type-reduction. Although this

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algorithm is iterative, it is very fast. These two methods are based on the calculation of the centroid.

Defuzzification: The second step of output processing, which occurs after type-reduction, is still called defuzzification. Because a type-reduced set of an Interval type-2 fuzzy set is always a finite Interval of numbers, the defuzzified value is just the average of the two end-points of this Interval. The outputs of the type reduction block are given to defuzzificaton block. The type- reduced sets are determined by their left end point and right end point, the defuzzified value is calculated by the average of these points. In a Type-1 FLS, output processing, called defuzzification, maps a type-1 fuzzy set into a number. There are many ways for doing this, e.g.,

by computing the union of the fired-rule output fuzzy sets (the result is another type-1 fuzzy set) and then computing the center of gravity of the membership function for that set; computing a weighted average of the center of gravities of each of the fired rule consequent membership functions; etc.

Things are somewhat more complicated for a Type-2 FLS, because to go from a Type-2 fuzzy setto a number (usually) requires two steps as shown in Figure 5.1. The first step, called type- reduction, is where a type-2 fuzzy set is reduced to a type-1 fuzzy set. In most engineering applications of a FLS, a number and not a fuzzy set is needed as its final output, e.g., the consequent of the rule given above is "Rotate the valve a bit to the right." No automatic valve will know what this means because "a bit to the right" is a linguistic expression, and a valve mustbe turned by numerical values, i.e. by a certain number of degrees. Consequently, the fired-rule output fuzzy sets must be converted into a number, and this can be done in the Figure 1 Output Processing block.

It is clear from Figure 4 that there can be two outputs to a type-2 FLS which are crisp numerical values and the type-reduced set. The latter provides a measure of the uncertainties that have flowed through the Interval type-2 FLS, due to the uncertain input measurements that have activated rules whose antecedents or consequents or both are uncertain. As standard deviation is widely used in probability and statistics to provide a measure of unpredictable uncertainty about a mean value, the type-reduced set can provide a measure of uncertainty about the crisp output of a type-2 FLS

V.SIMULATION RESULTS

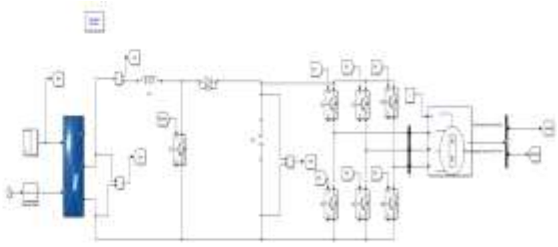


Fig.5 MATLAB/SIMULINK circuit diagram of the solar water pumping system.

A) EXISTING RESULTS

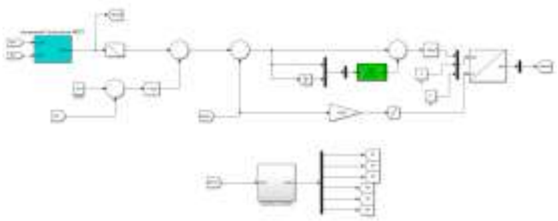
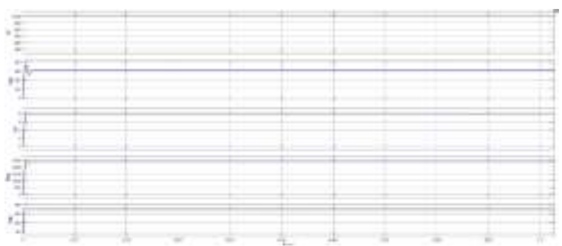
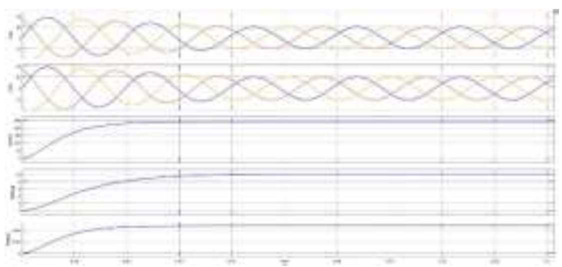


Fig.6 Control system with FLC



(a)



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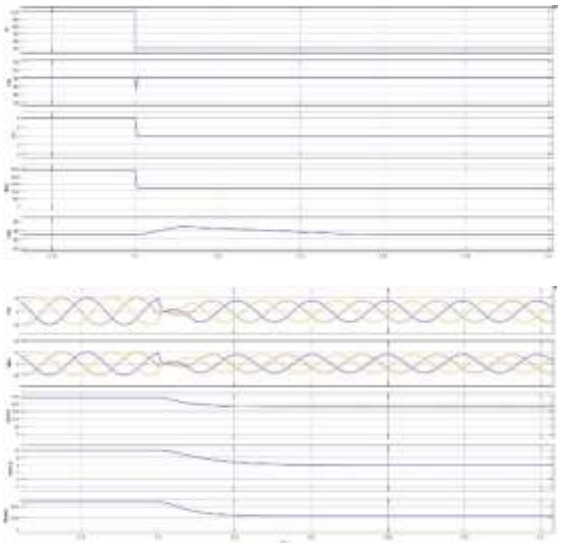
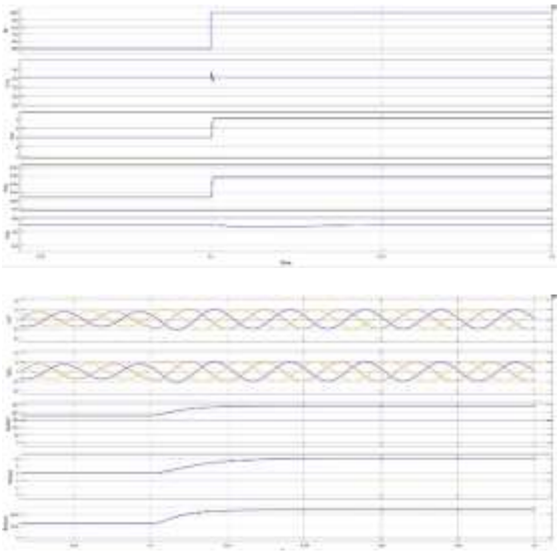
(b)

Fig.7 Starting and steady state performance of (a) solar PV parameters and (b) PMSM parameters



(a)



(b)

Fig. 8 Dynamic performance during insolation change (a) from 1000 W/m2 to 500 W/m2 (b) from 500 W/m2 to 1000 W/m2

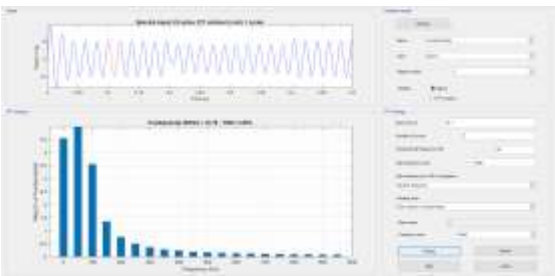


Fig.9 Motor current THD%

B) EXTENSION RESULTS

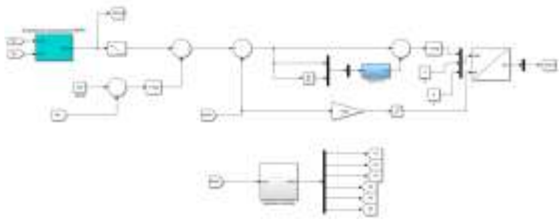
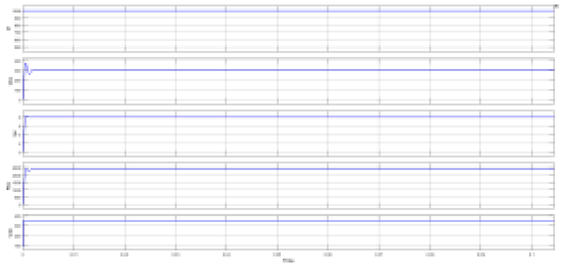
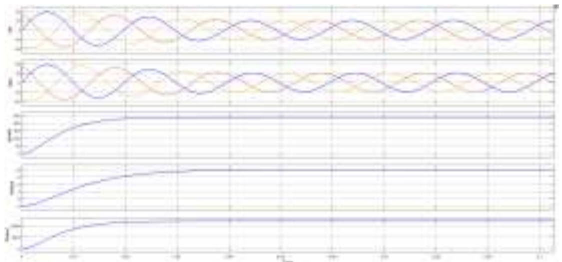


Fig.10 Control system with tyope-2 FLC

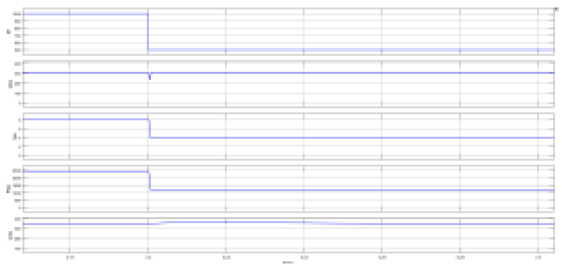


(a)



(b)

Fig.11 Starting and steady state performance of (a) solar PV parameters and (b) PMSM parameters



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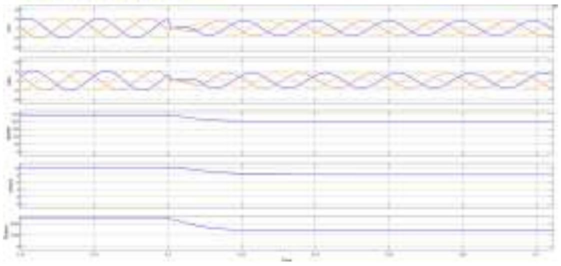
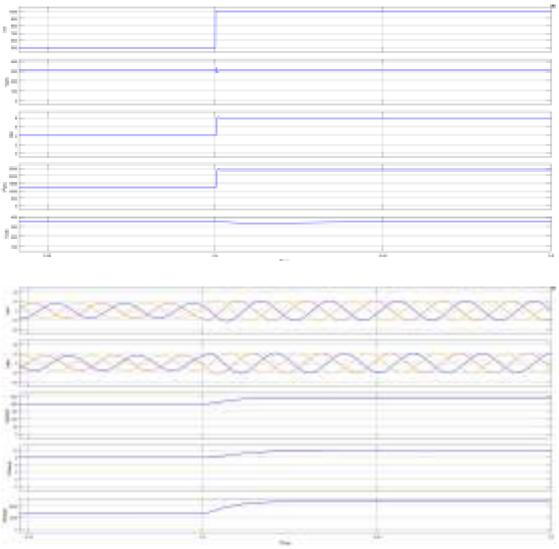


(a)



(b)

Fig.12 Dynamic performance during insolation change (a) from 1000 W/m2 to 500 W/m2 (b) from 500 W/m2 to 1000 W/m2

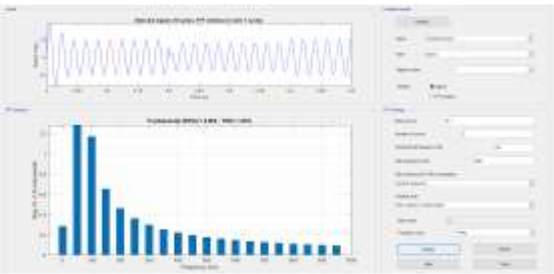


Fig.13 Motor current THD%

CONCLUSION

A solar PV array powered PMSM driven water pumping system by using Type-2 FLC is modelled and the performance is realized through simulation validation. The variation of various system parameters, has been studied during starting and steady state at STC and under wide range of solar insolation change. Acquired results depict that the presented system performs satisfactorily under all operating conditions. An introduction of Type-2 FLC based error component along with actual speed error, has improved the speed response of the system. The presented hybrid PI control has eliminated the peak overshoot during dynamic condition and chattering during steady state condition. An incorporation of solar PV feed-forward term, has accelerated the system response under dynamic condition. The use of PMSM has improved the efficiency of the system. Hence the presented system gives a fast, efficient, and reliable solution for solar water pumping and compered to existing system the proposed system gives less THD.

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