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Investigation of High gain MIC power converter for multicrystal PV module employing fuzzy logic technique

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Original scientific paper

A Mutual Inductive Coupled (MIC) DC-DC power converter circuit for Photo-Voltaic (PV) system employing fuzzy logic based maximum power point tracking is presented in this research paper. The proposed DC-DC converter has been modelled and simulated using Matlab-simulink environment for obtaining high gain. The mutually coupled inductor uses one core instead of two or more, which reduces size of the converter. A passive regenerative snubber is exploited for absorbing the energy of stray inductance and also the capacitors are charged in parallel and discharged in series through the mutual coupled inductor for achieving high voltage gain of this converter. The voltage gain characteristics of the MIC converter have been studied for various coupling coefficient, turns ratio of two-winding mutual inductor and duty cycle. Moreover, PV system is conveniently interfaced with proposed power converter for maximizing the solar energy yield and analysed by employing Perturb & Observe (P&O) and fuzzy logic based MPPT algorithms under various operating conditions. The obtained results reveal that, the fuzzy controller provides good improvement in tracking of maximum power and helps to extract considerable amount of additional solar energy from a PV module as compared with P&O algorithm.

Key words: Photo-Voltaic system, Perturb & Observe algorithm, Mutual – Inductive Core, Fuzzy Logic Control.

Istraživanje pretvarača sa spregnutim međuinduktivitetom za više-kristalne fotonaponske sustave s velikim pojačanjem korištenjem neizrazite logike. U ovome radu prikazan je DC-DC pretvarač sa spregnutim međuinduktivitetom (MIC) za fotonaponske (PV) sustave izveden uz praćenje optimalne radne točke korištenjem neizrazite logike. Predloženi DC-DC pretvarač modeliran je i simuliran korištenjem Matlab-simulink okruženja za velika pojačanja. Spregnuti međuinduktivitet koristi jednu jezgru umjesto dvije ili više njih, što umanjuje veličinu pretvarača. Pasivna regenerativna prigušnica je korištena za apsorpciju energije lutajućih struja te su kondenzatori punjeni u paraleli i pražnjeni u seriji kroz spregnuti međuinduktivitet u svrhu ostvarivanja velikog naponskog pojačanja pretvarača. Karakteritike naponskog pojačanja MIC pretvarača su proučavane za različite koeficijente spregnutosti, omjer zakretaja dvostruko namatanih međuinduktiviteta i trajanje ciklusa. Nadalje, PV sustav je prigodno povezan s predloženim pretvaračem za optimiranje doprinosa solarne energije i analiziran korištenjem algoritma perturbiranja & razmatranja (P&O) te MPPT algoritma zasnovanog na neizrazitoj logici za različite uvjete rada. Rezultati prikazuju da neizraziti regulator pruža napredak u praćenju optimalne radne točke i pomaže pri izlučivanju zamjetne količine dodatne solarne energije iz PV modula u usporedbi s P&O algoritmom.

Ključne riječi: Fotonaponski sustav, algoritam perturbiranja & razmatranja, zajednička induktivna jezgra, neizrazita upravljačka logika.

1 INTRODUCTION

In the present scenario, increasing pollution, CO_2 emission and global warming is a big threat for our earth. PV system offers an environmental friendly renewable energy source of electricity, in which the fuel is sunshine. Every day, the sun delivers energy to the earth at free of cost. Photo-Voltaic technologies use this free green energy and convert photonic energy into electricity. Generating electricity from solar PV system helps to control the energy inflation and gives increased autonomy- independence from the grid or backup during power outages. The PV systems can be effectively installed on the roofs of buildings and houses to supply electricity for lighting and to run many appliances [1]. In remote locations, PV systems are more reasonable alternative resource for electrical power generation than erection of long transmission lines to connect with an electrical grid. Since, the efficiency of the PV cell is very low and it is mandatory to introduce the power converter circuit along with the MPPT (Maximum Power Point Tracking) algorithm [2-4] to improve the per-

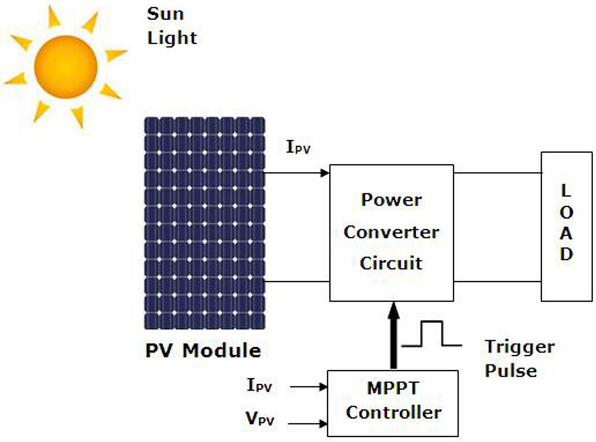


Fig. 1: MIC power converter for photovoltaic energy system using MPPT controller.

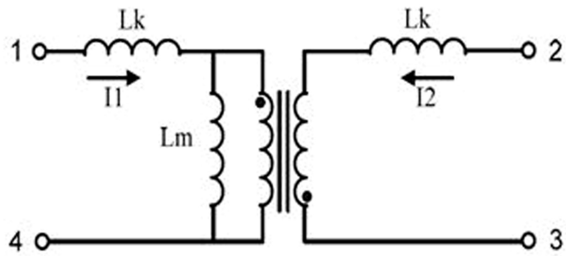


Fig. 2: The equivalent circuit diagram of a two - winding mutual inductor core.

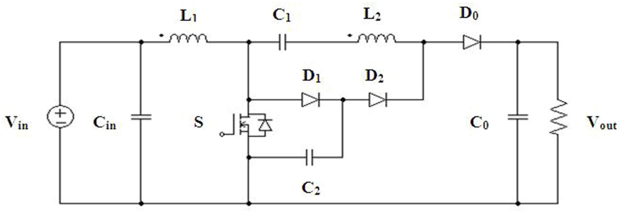


Fig. 3: The proposed MIC DC-DC power converter circuit.

formance of the PV system. In this paper, the performance of a MIC power converter for photovoltaic energy system using P&O and fuzzy logic model has been developed and evaluated in the Matlab-simulink environment. Figure 1 shows the MIC power converter for photovoltaic energy systems with MPPT controller. The output voltage of this proposed system is controlled by proper adjustment of duty cycle (D) of the power converter circuit.

Due to nonlinear behavior and low energy conversion efficiency of PV module, it must always be operated at the Maximum Power Point (MPP) to improve the performance of the PV system. The P&O algorithm is the one among the most popular conventional algorithms, mostly suitable for steady state condition only where the solar irradiation and temperature condition changes slowly. In this research work, a multicrystal PV module is connected to power converter with fuzzy MPPT controller, which finds and maintains the operation of the system at the MPP for different operating conditions of the PV system and to extract the maximum possible solar energy. The knowledge-base of fuzzy controller is exposed here. The obtained simulated results reveal that the additional power is extracted from a PV module by employing fuzzy logic controller than P&O.

2 MATHEMATICAL MODELING OF MIC CONVERTER

Figure 2 shows the equivalent circuit diagram of a two-winding mutual inductor core with a magnetizing inductor (L_m) and an equivalent leakage inductor (L_k) which, stores the energy during the switching cycle period of the converter [5,6].

The primary(N_1) and secondary(N_2) winding turns of the coupling co-efficient (k) and turns ratio (n) of two-winding mutual inductor helps to produce high voltage gain and are expressed in (1) and (2)

$$n = \frac{N_2}{N_1} \tag{1}$$

$$k = \frac{L_m}{L_k + L_m} \tag{2}$$

For higher value of duty cycle, the conventional boost converter is not able to give a high gain and causes more conduction losses in the system. Moreover, cascading of several conventional boost converters may give higher output voltage but, it requires a larger volume and weight of the capacitance increases. This lowers the efficiency of the system and it is also expensive [7, 8]. The voltage lift technique [9, 10] may give high gain but the main switch suffers a high transient current and hence the conduction loss is also increased. Here, a mutual inductance with a lower voltage rated switch and passive regenerative snubber circuit are used, to promote the high voltage profile and it also avoids the stray inductance, diode reverse recovery problems. Figure 3 shows the MIC DC-DC power converter circuit.

The voltage across the switch (S), the primary - secondary mutual inductance ($L_1\&L_2$) and the leakage inductor (L_k) are denoted as V_{ds}, V_{Lm} and V_{Lk} respectively. The primary current (i_{L1}) of the coupled inductor is composed of the magnetizing current (i_{Lm}) and the primary induced current (i_1). The Kirchhoff's Voltage Law (K_{VL}) & Kirchhoff's Current Law (K_{CL}) are used to develop the mathematical formulation with the assumption that, the conductive voltage drop across the diodes and the switch are neglected. The mathematical model equations have been developed during turn ON & turn OFF period of the converter performance in one complete switching cycle. During turn ON period, the voltage across the magnetizing inductor (L_m), secondary winding of the coupled inductor (L_2) and capacitor (C_2) can be expressed in (3), (4) and (5)

$$V_{Lm} = kV_{in} \tag{3}$$

$$V_{L2} = nV_{Lm} = nkV_{in} \tag{4}$$

$$V_{C2} = nkV_{in} + V_{C1} \tag{5}$$

During turned OFF period of switch, the design equations for voltages across leakage inductor, magnetizing inductor and clamped capacitor (C_1) are represented as follows:

$$V_{Lk} = \frac{D(n+1)(1-k)}{2(1-D)} V_{in} \tag{6}$$

$$V_{Lm} = \frac{DkV_{in}}{(1-D)} \tag{7}$$

$$V_{C1} = V_{Lk} + V_{Lm} + V_{in} \tag{8}$$

$$V_{Lk} = \frac{V_{in}}{(1-D)} + \frac{D(n+1)(1-k)}{2(1-D)} V_{in} \tag{9}$$

The voltage across the high-voltage capacitor and the secondary winding of the coupled inductor can be represented as follows:

$$V_{C2} = \left[\frac{2 + D(n-1)(1-k)}{2(1-D)} + nk \right] V_{in} \tag{10}$$

$$V_{L2} = nV_{Lm} = \frac{DnkV_{in}}{(1-D)} \tag{11}$$

The output voltage (Vout) is computed as summation of voltage across the elements L2, C1 & C2. The simplified form of Vout is expressed in (13) as below:

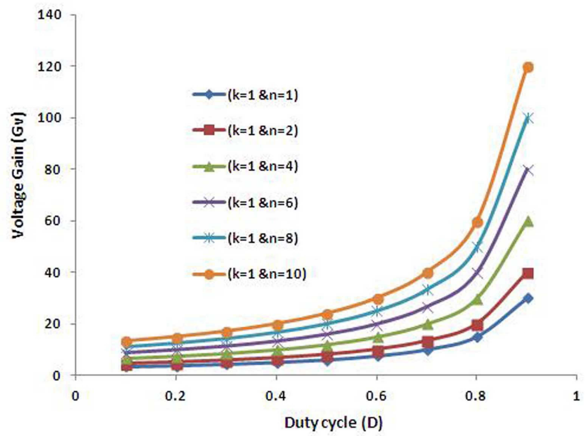
$$V_{out} = V_{L2} + V_{C1} + V_{C2} \tag{12}$$

$$V_{out} = \frac{2+nk}{1-D} V_{in} + \frac{D(n-1)(1-k)}{(1-D)} V_{in} \tag{13}$$

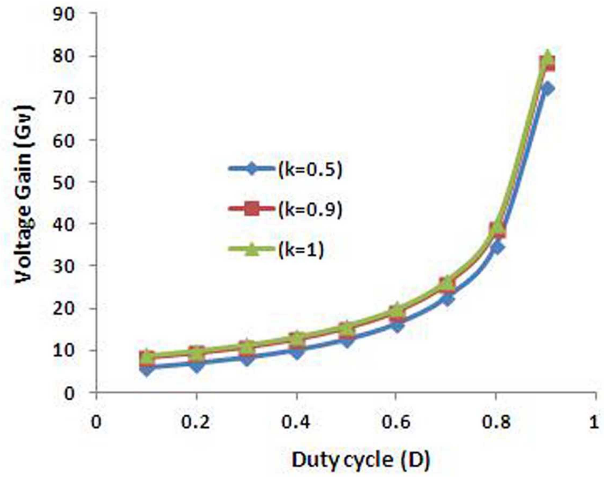
The voltage gain (G_v) is derived from output equation which is greatly depends on the duty cycle (D), turns ratio (n) and the coupling coefficient (k). The voltage gain of the converter is represented in (14)

$$G_V = \frac{V_{out}}{V_{in}} = \frac{2+nk}{1-D} + \frac{D(n-1)(1-k)}{(1-D)} \tag{14}$$

The voltage gain versus duty cycle is plotted for various turn ratio ($n = 1, 2, 4, 6, 8 \,\&\, 10$) by keeping $k = 1$ in Fig. 4a. It is also plotted for various k value keeping $n = 6$ in Fig.4b. From Fig.4a it is observed that increase in turns ratio increases the voltage gain of the converter drastically.



(a) Voltage gain characteristics curve for $k = 1$.



(b) Voltage gain characteristics curve for $n = 6$ and $k = 0.5, 0.9 \,\&\, 1.0$.

From Fig.4b it is observed that the voltage gain is less sensitive to the coupling coefficient and it can be taken as '1' which further simplifies (8) and (14) as below:

$$V_{C1} = \frac{V_{in}}{(1-D)} \tag{15}$$

$$G_V = \frac{V_{out}}{V_{in}} = \frac{2+n}{1-D} \tag{16}$$

$$V_{DS} = \frac{V_{out}}{(n+2)} \tag{17}$$

By the above (17), it is found that the switch voltage depends on the output voltage and the turns ratio but not on the input voltage source (V_{in}) and the duty cycle. Hence, the switching losses are reduced.

2.1 Simulation of converter circuit

The simulink model of the MIC converter circuit has been developed under Matlab environment as shown in Fig.5.

During the switching, the input voltage source charges the magnetizing inductor and hence the magnetizing current increases gradually. Also, the high-voltage capacitor is charged gradually by series combination of secondary voltage and the clamped capacitor voltage through the switch (S) and the rectifier diode. The design specifications of converter circuit are tabulated in Table 1. The simulation results of primary inductance current (I_{L1}), secondary inductance current (I_{L2}), Diode ($I_{D1}\&I_{D2}$) current, switch voltage (V_{ds}) and switching current (I_{ds}) of the MIC converter are illustrated in Fig.6.

Table 1: Design specifications of the converter

Design parameters	**Values**
Switching Frequency (f_S)	100 kHz
Primary winding Inductor (L_1)	$13\,\mu$H
Secondary winding Inductor (L_2)	$470\,\mu$H
Coupling Coefficient (k)	0.98
Turns Ratio (n)	$6\,(3:18)$
Number of primary winding	3
Number of Secondary winding	18
Input Capacitor (C_{IN})	$3300\,\mu$F
Clamped Capacitor (C_1)	$5\,\mu$F
High Voltage Capacitor (C_2)	$6.8\,\mu$F
Output Capacitor (C_0)	$47\,\mu$F

Figure 7 shows the input-output simulation response of converter where, the output voltage (V_{out}), output power (P_{out}) and voltage gain ratio is observed as 192.1 Volts 12.3 Watts and 16 respectively for the input voltage (V_{in}) of 12 V & duty cycle as 0.5. This converter is suitable for the solar based power generation because, the input fluctuations (G-Solar irradiation W/m2 & T-Temperature °C) in the non-linear nature of solar energy is accounted and makes the converter to operate effectively by employing P&O and Fuzzy based MPPT algorithms which are discussed in the next section.

3 MPPT CONTROLLER OVERVIEW

MPPT helps to extract the maximum possible power from solar energy continuously and delivers it to the load. To operate the PV panel to its maximum efficiency, it is important to operate at the unique point where it matches with the panel output to its load and it is referred as equilibrium operating peak point of the system. This operating point get shifted with the non-linearity behavior of the photovoltaic system and it should be tracked for all the times using MPPT algorithm for obtaining the better performance. The Perturb & Observe, Incremental Conductance (IC), fractional open-circuit voltage and fractional short-circuit current are several conventional MPPT control techniques to track the MPP of the PV systems. Here, the P&O algorithm is implemented and the simulated results are compared with fuzzy controller system.

3.1 P&O MPPT Algorithm

The MPPT algorithm is modeled using embedded Matlab function block and it senses the voltage and current of the PV module and adjusts the duty ratio according to P&O algorithm. In, P&O algorithm the operating voltage of the Photovoltaic module is perturbed by a small amount and the observed solar power (ΔP) is positive means, the direction is moving towards MPP and the perturbation should be continued in the same direction. Otherwise, if ΔP is negative, it deviates from the MPP and the sign of perturbation should be changed. A common problem in P&O algorithm is that the output response is oscillatory around the MPP under low irradiance and slow response to rapid changes in irradiance & temperature which results in more power losses in the PV system [11]. The P&O algorithm has been analyzed and the maximum tracked power is noticed as 179.28 Watts and 126.60 Watts for $G = 1000$ W/m2 & $T = 25$ °C and $G = 800$ W/m2 & $T = 40$ °C respectively and are shown in Fig.8 and Fig.9.

3.2 Fuzzy logic based MPPT controller

Fuzzy Logic Control (FLC) is one of the most powerful controlling tools and it is related to the human being's feeling and inference process [12]. Fuzzy control strategies are highly potential due to its adaptive structure and fast computation capability. The Fuzzy logic model is merely a representation of the human cognitive and decision making process, hence developing and tuning of the Fuzzy Inference System (FIS) is more intuitive than the PID controller. Also Fuzzy controller has the capability to determine its parameters even under imprecise data, complicated mathematical model and operates with highly nonlinear system. PID controller has less robustness against uncertainty for nonlinear systems. But fuzzy controller will decrease the effect of uncertainty better than conventional controllers. Moreover, solar energy system is having nonlinear behaviour due to the change in solar irradiation and temperature over the period of time, results in mismatch of Current-Voltage (I-V) characteristics of the PV module. For sudden changes in operating conditions, MPPT with PID controllers will be more difficult to track MPP. The fuzzy controller provides good improvement in tracking of maximum power and helps to extract considerable amount of solar energy from a PV module. Hence, Fuzzy Logic Control based MPPT controller is a good alternative to a conventional PID controller. Moreover, it reduces the

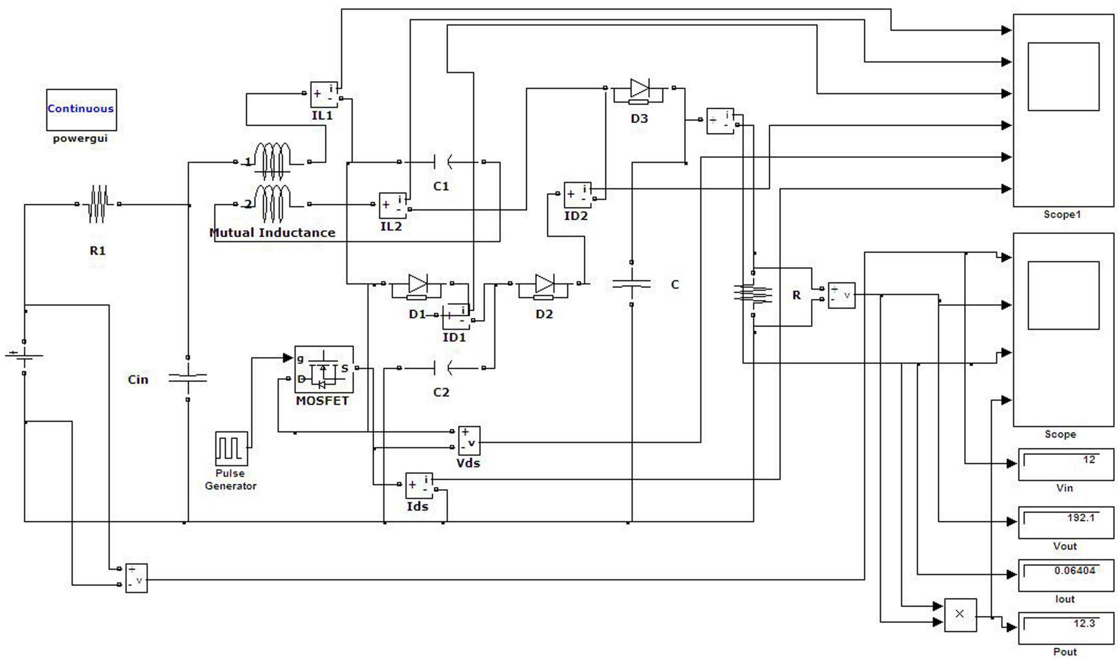


Fig. 5: The Matlab-Simulink model of the MIC converter.

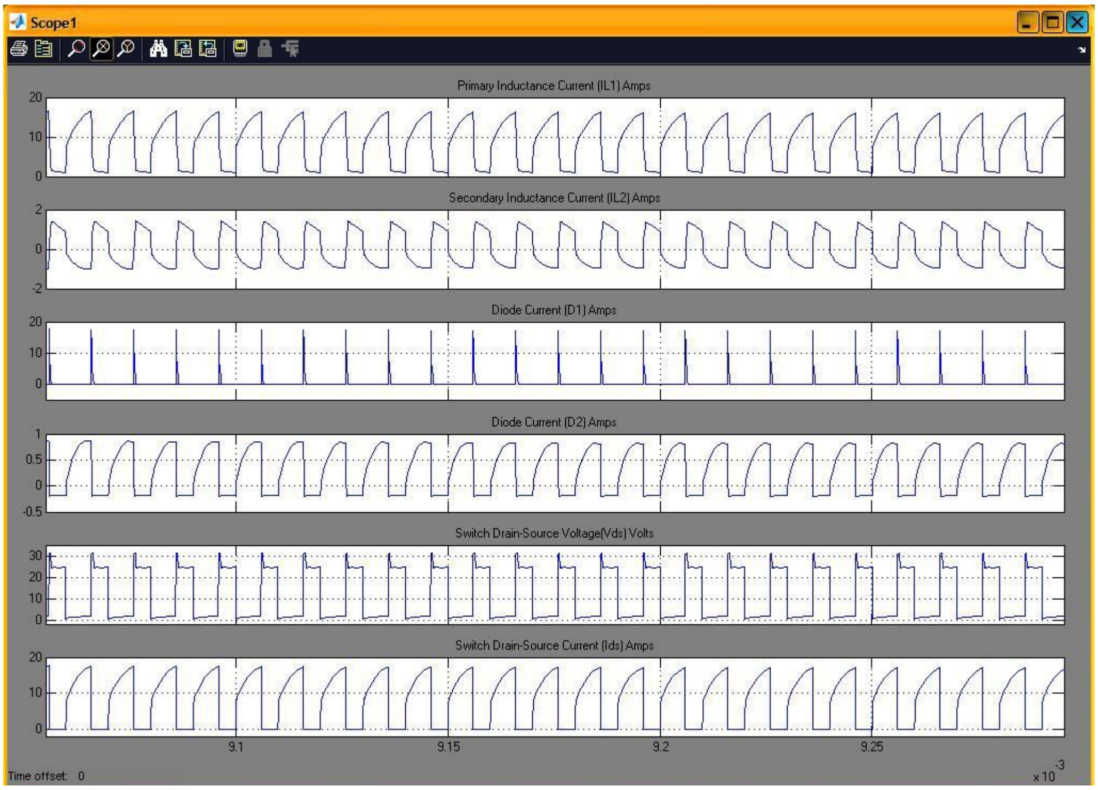


Fig. 6: Simulation results of primary inductance current (IL_1), secondary inductance current (IL_2), Diode (ID_1&ID_2) current, switch voltage (V_{ds}) and switching current (I_{ds}).

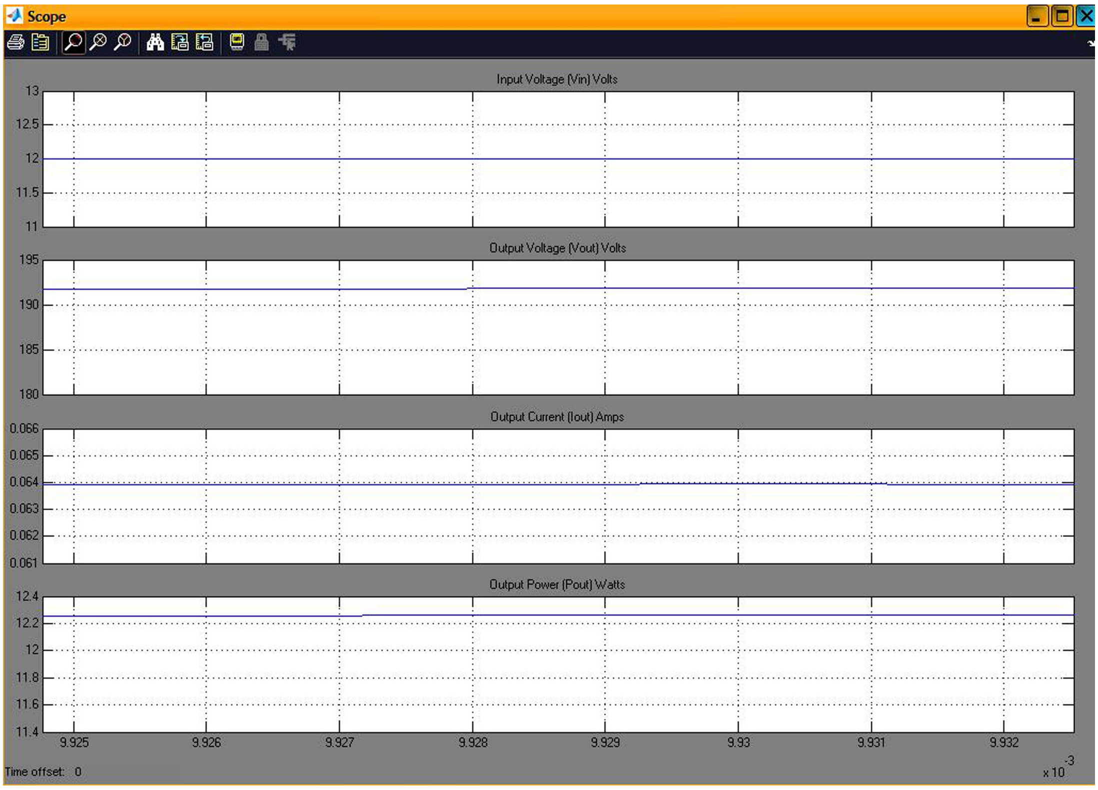


Fig. 7: Matlab-Simulation response of the converter.

steady state oscillations once the MPP has been located and it has the ability to track the MPP during large fluctuations in the operating conditions. Thus having a controller with a high flexibility is very important. This is actual reason for the use of Fuzzy Logic Controller to analyze our proposed power converter for multicrystal PV module when compared with other conventional controllers.

3.2.1 Fuzzy logic block diagram

Figure 10 shows the block diagram representation of FLC where it has error (E) and change of error (CE) as two input variables and change of duty ratio as one output variable.

The two input variables of FLC are expressed by (18) and (19) as below:

$$Ej = \frac{(Ppv(j) - Ppv(j-1))}{(Vpv(j) - Vpv(j-1))} \tag{18}$$

$$CE(j) = E(j) - E(j-1) \tag{19}$$

where $P_{pv}(j)$, $V_{pv}(j)$ are the PV power and voltage respectively at instant j. E (j) is the load operating point at that instant j and it is located on either left or right of the MPP on the P-V characteristic & it is equal to zero at MPP. The change of error CE (j) expresses the direction of this moving point . The error (E) and rate of change of error (CE) signals of fuzzy controller produces a control signal for the pulse width-modulation (PWM) generator which in turn adjusts the width of the duty cycle ratio (D) to trigger the converter switch so that the PV system extracts maximum power under various operating conditions. Mamdani fuzzy inference method is adopted here and it has significant capability for many applications.

3.2.2 Fuzzification

The Fuzzification is the method of converting the system actual input error (E) and change in error (CE) into linguistic fuzzy sets by employing fuzzy membership function. These variables are stated in terms of five linguistic variables: NH (Negative High), NL (Negative Low), ZR (Zero), PL (Positive Low) and PH (Positive High). The fuzzy rules are implemented with the help of membership functions. The symmetric triangular membership function is considered for this analysis to graphically represent the magnitude of participation of each input.

3.2.3 Rule base and inference engine

The Fuzzy rule base has been developed by the group of If-Then rules which has all the relevant information for the

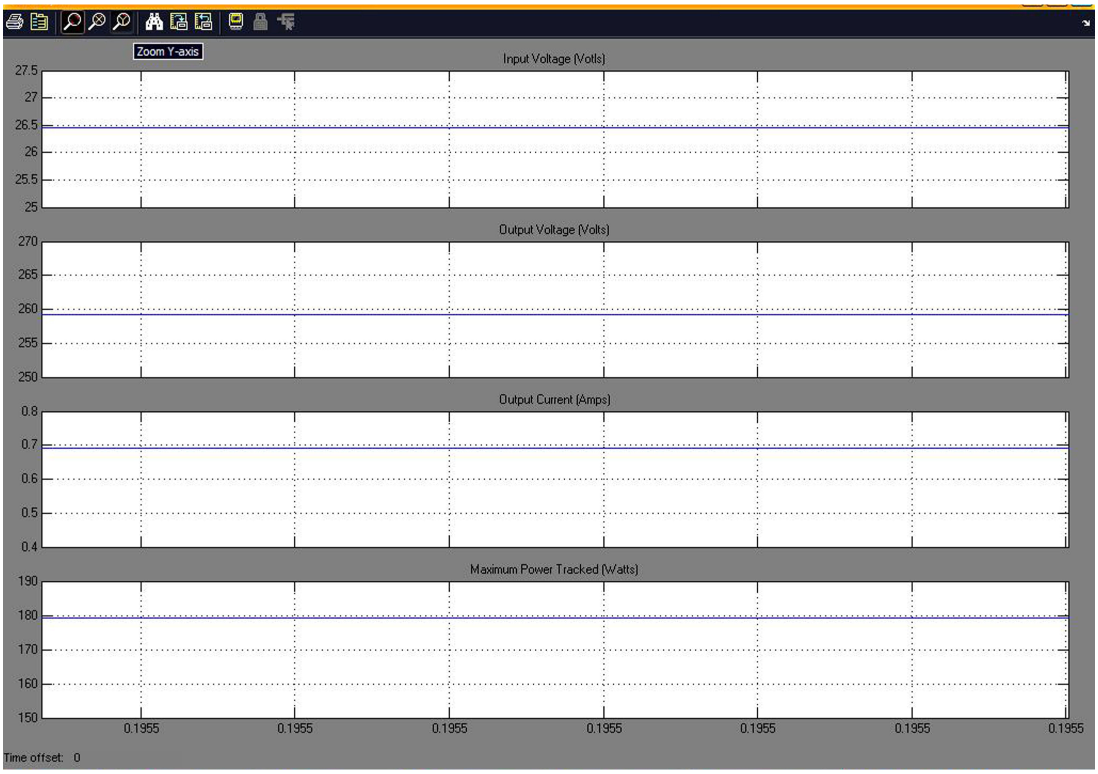


Fig. 8: Matlab – simulation response of P&O algorithm for $G = 1000$ W/m2 & $T = 25°$C.

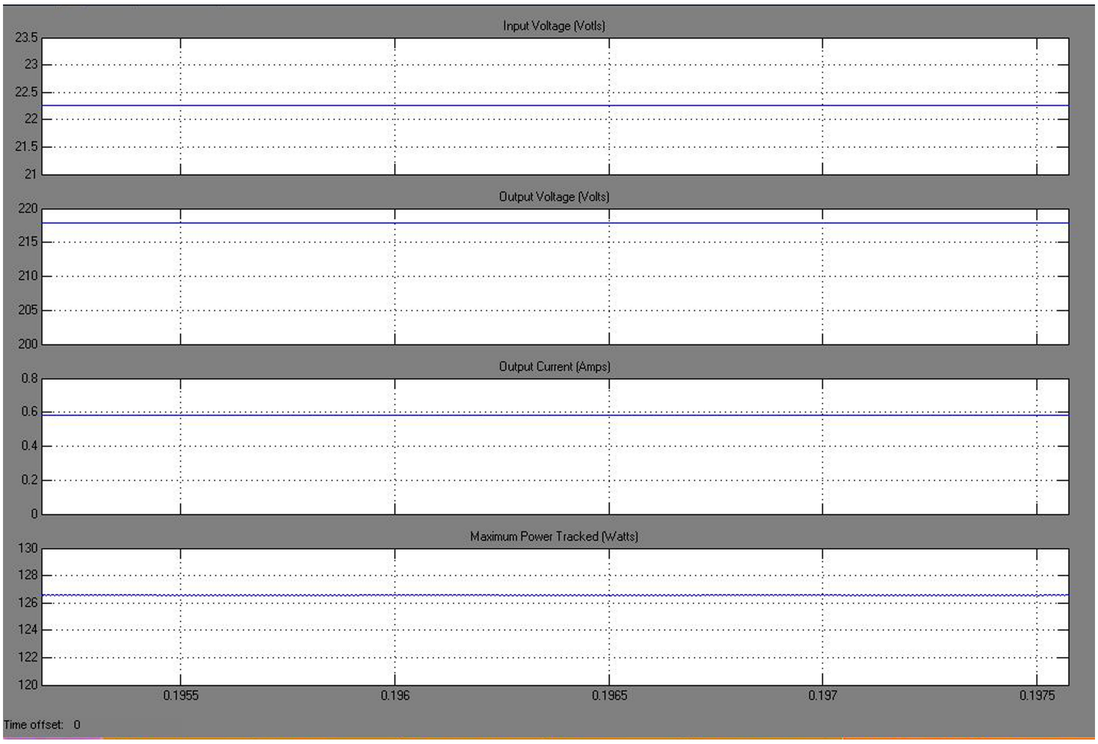


Fig. 9: Matlab – simulation response of P&O algorithm for $G = 800$ W/m2 & $T = 40°$C.

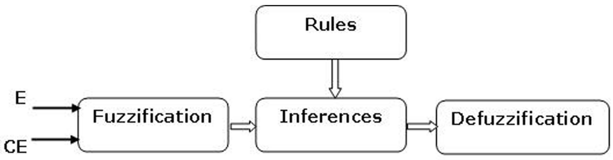


Fig. 10: Block diagram representation of FLC.

controlling the parameters [13]. In this research work, the fuzzy rules have been developed by considering the following overall tracking performance in mind.

- the change of D should be maintained at zero, when the PV panel voltage is equal to the V_{mp}.
- when the panel voltage is near to V_{mp} and is approaching it rapidly, then the change of D should be zero so as to prevent operating point deviation away from V_{mp}.
- the incremental D is small, when the panel voltage is close to reference voltage V_{ref}.
- the change of D is negative and it must be large so as to bring the terminal voltage to V_m, when the terminal voltage is less than the V_{mp}.
- when the terminal voltage is much greater than V_{mp}, then change the D of the mutual – inductive coupled converter so as to bring the terminal voltage to V_{ref}.

By considering the above information, the fuzzy rules are formulated and the corresponding rule base is tabulated in Table 2 for enhancing the performance of the PV system by extracting the maximum power from the solar panel.

Table 2: Fuzzy rule base

CE / E	NH	NL	ZR	PL	PH
NH	ZR	ZR	PH	PH	PH
NL	ZR	ZR	PL	PL	PL
ZR	PL	ZR	ZR	ZR	NL
PL	NL	NL	NL	ZR	ZR
PH	NH	NH	NH	ZR	ZR

The fuzzy rules use the input membership values as weighting parameter to establish their control on the fuzzy output sets. For example, If E is NH and CE is ZR then crisp D is PH, it means that if the operating point is far away from the maximum power point by the right side, and the deviation of the slope of the curve is almost zero and then increases the duty cycle. After, the functions have been inferred, scaled and combined to find a crisp value which controls the system through the defuzzification process.

3.2.4 Defuzzification

The Center of Gravity method (COG) is the most popular defuzzification technique which is applied here, to determine the output of FLC with crisp value of the change of duty cycle. The variables μ, membership function and D_j, the universe, may be discretized into j equal numbers of subintervals by the point D_1, D_2, $D_3 \ldots D_n$. D is a crisp value, which is defuzzifed value of the duty cycle.

$$D = \frac{\sum_{j=1}^{n} \mu \ \times \ D_j \ - D_j}{\sum_{j=1}^{n} \mu \ \times \ D_j} \tag{20}$$

3.3 Results and discussion

The PV module has been modeled in Matlab-simulink environment along with FLC as shown in Fig.11. The PV module parameters are referred from manufacture's data sheet (KC200GT) which provides information about the performance characteristics of PV module. The peak power tracking (P_{max}) effectiveness and conversion efficiency of the converter for different operating condition is studied through the comparison of Fuzzy and P&O methods and which are tabulated in Table 3.

The Figure 12 and Figure 13 are show the maximum tracked power as 195.05 Watts and 135.01 Watts for $G = 1000\,\mathrm{W/m2}$ & $T = 25\,°\mathrm{C}$ and $G = 800\,\mathrm{W/m2}$ & $T = 40\,°\mathrm{C}$ respectively using Fuzzy MPPT. Thus, the MPPT using fuzzy logic improves the performance of the system by means of better tracking of solar power and efficiency. The results revealed that the Fuzzy based MPPT gives the better efficiency & peak power tracking than P&O algorithm for the same operating conditions, which is shown in Fig. 14. The developed PV system can be used for high power applications like high intensity discharge lamps in automobiles and sports fed lights. Further it can also be connected with the electrical power grid system through a standard inverter to meet the increasing power demand.

3.4 CONCLUSION

In this research paper, a Mutual Inductive Coupled power converter circuit has been investigated for PV system under different operating conditions by employing fuzzy logic based maximum power point tracking scheme. The proposed MIC converter is modeled using the coupled inductor core in Matlab-simulink environment. The voltage gain characteristics have been studied for the different coupling co-efficient, turn's ratio of two-winding mutual inductor and duty cycle. The obtained result shows that, for the same duty cycle the voltage gain of this converter is high as compared to the conventional boost converter. This converter topology promotes high gain for photovoltaic applications and prevents the leakage inductance and reverse recovery problem. Moreover, the MIC power converter interfaced with the PV system are analysed by employing P&O

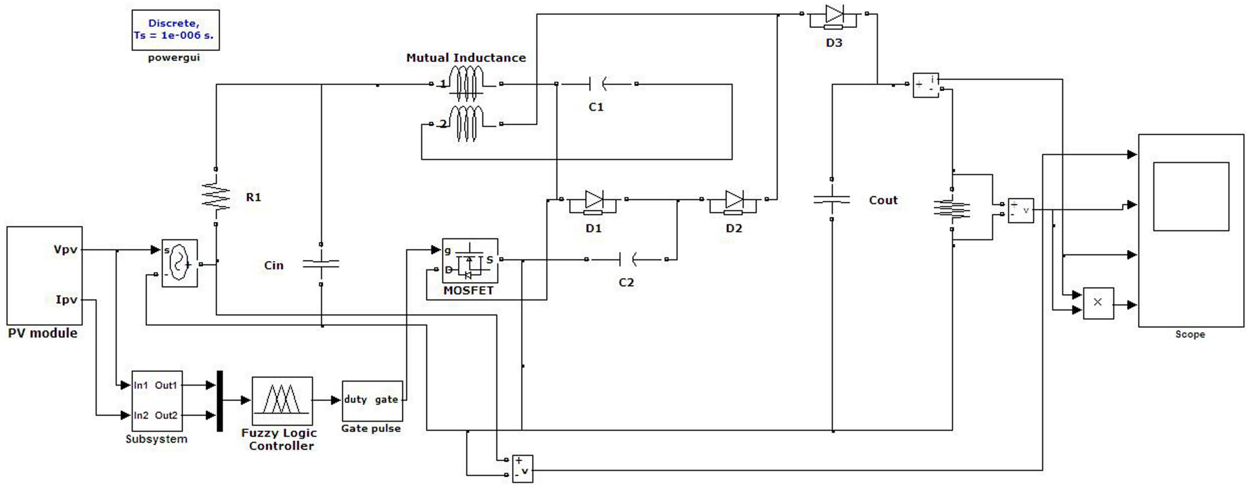


Fig. 11: Matlab -Simulink model of PV system with Fuzzy Logic Control.

Table 3: Performance analysis of MIC converter using P&O and Fuzzy MPPT methods for different operating Conditions

Operating Conditions	I_{PV} **(Amps)**	V_{PV} **(Volts)**	P_{in} **(Watts)**	**MPPT Controller**	I_{out} **(Amps)**	V_{out} **(Volts)**	**Tracked** P_{out} **(Watts)**	**Converter efficiency** (η)
$G = 1000$ W/m2 & $T = 25\,°$C	7.561	26.46	200.1	P&O Fuzzy	0.6914 0.7211	259.3 270.5	179.28 195.05	89.60 97.47
$G = 1000$ W/m2 & $T = 35\,°$C	7.357	25.75	189.4	P&O Fuzzy	0.6726 0.695	252.2 260.5	169.60 181.05	89.55 95.59
$G = 800$ W/m2 & $T = 25\,°$C	6.368	22.29	141.9	P&O Fuzzy	0.5823 0.6008	218.1 225.42	127.0 135.43	89.49 95.44
$G = 800$ W/m2 & $T = 40\,°$C	6.362	22.27	141.7	P&O Fuzzy	0.5811 0.6001	217.9 225.0	126.60 135.01	89.34 95.27
$G = 600$ W/m2 & $T = 25\,°$C	4.782	16.74	80.05	P&O Fuzzy	0.398 0.4253	149.2 159.49	59.38 67.83	74.18 84.74

and fuzzy logic MPPT techniques under various operating conditions. The simulated results showed that, the fuzzy based MPPT provides better tracking and extracts significant amount of solar energy from a photovoltaic module than P&O algorithm under all operating conditions.

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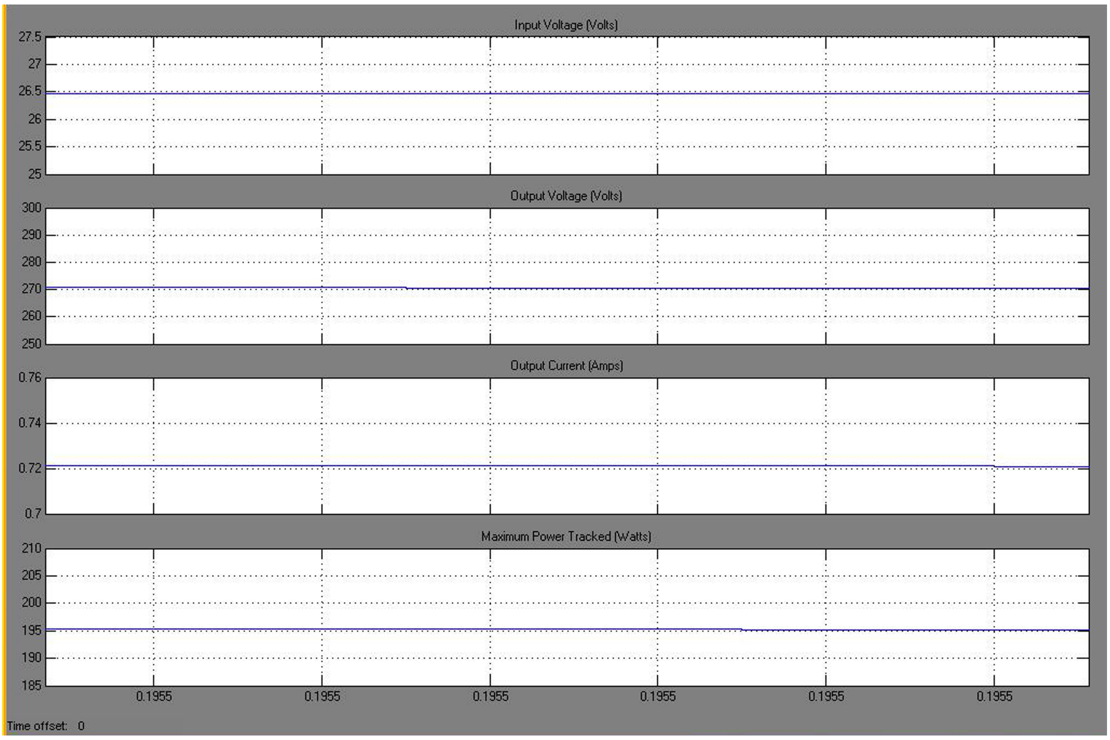

Fig. 12: Matlab – simulation response of Fuzzy MPPT algorithm for $G = 1000\,$W/m2 & $T = 25°$C.

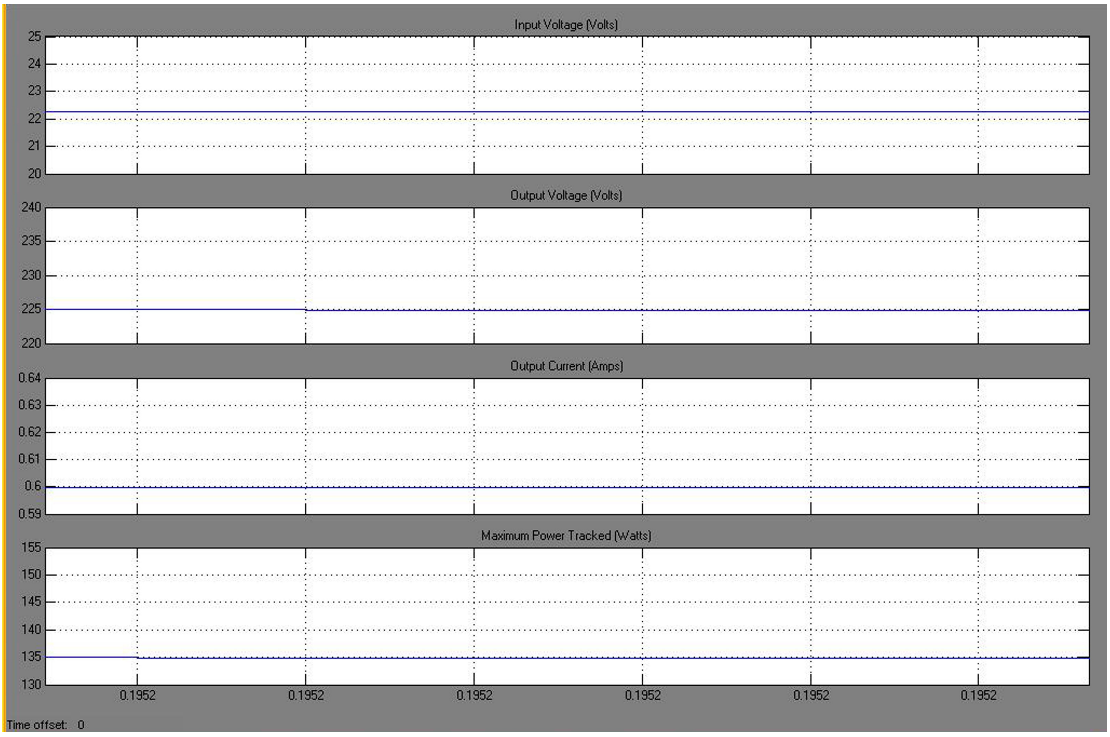

Fig. 13: Matlab – simulation response of Fuzzy MPPT algorithm for $G = 800\,$W/m2 & $T = 40°$C.

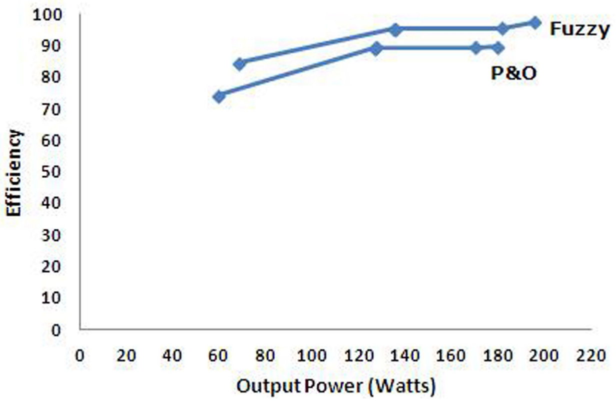

Fig. 14: The efficiency of MIC converter using P&O and FLC techniques.

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