Comparison of regular and irregular 32 pulse density modulation patterns for induction heating

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Abstract

In this study, an induction heating (IH) application is carried out by transferring the maximum power extracted from photovoltaic (PV) panels to the stainless steel with the designed regular and irregular 32 pulse density modulation (PDM) controlled series resonant inverter. The main objective of this study is to analyse the changes in the system due to regular and irregular PDM patterns. Maximum power point tracker (MPPT) is used to control the output power at different solar irradiation values with varying PDM patterns. Regular and irregular PDM control methods are compared in terms of MPPT efficiency, cost, algorithm complexity, logic control structure and current/voltage stresses of the power switches. Zero current switching (ZCS) conditions are provided by using phase locked loop (PLL) technique at all power points of the PV system. The appropriate switching conditions are tracked continuously at resonant frequency, and therefore soft switching is realised. Perturb and observe (P&O) algorithm is used with the aim of tracking the maximum power in PV panels and high tracking efficiency is obtained with PDM-controlled P&O MPPT algorithm. ATMEL328P-AU microcontroller is used to control the inverter in the system.

1 | INTRODUCTION

The interest in renewable energy resources has increased with the increasing demand for energy. In particular, with the investments on photovoltaic (PV) systems used to obtain electricity from the sun, this sector has taken more attention. PV systems are used in many areas such as irrigation, housing and industry applications [1]. In PV systems, energy is provided by using PV panels. However, the low efficiency of PV panels increases the cost of these systems. Another disadvantage is that the power of PV panel changes continuously due to changes in weather conditions (temperature, solar irradiation). In order to solve this problem, the output of the PV panels is desired to be at maximum power. For this purpose, maximum power point tracker (MPPT) algorithms are used in DC–DC or DC–AC power converters [2, 3]. Many MPPT algorithms are used to track the maximum power point (MPP). However, perturb and observe (P&O) algorithm, which is used widely, provide higher tracking efficiency. P&O algorithm is preferred mostly since the system is independent from PV panel [4, 5].

Induction heating (IH) is a technique based on the generation of eddy currents in the metal part within the magnetic field and the emergence of these currents as heat in the workpiece. The high frequency magnetic flux required for IH is obtained by resonant circuits. When a coil is wrapped in accordance with the workpiece to be heated and the current with desired amplitude and frequency required by this coil is passed, energy is transferred to the workpiece through induction. Therefore, heating process is achieved quickly by providing partial heating and without heating all the workpiece [6, 7]. In the process of IH of a workpiece, circuit parameters are very important. Equivalent circuit parameters differ according to the material, the temperature and position of the workpiece. The output power and switching losses of the circuit are directly related to the equivalent circuit parameters. Therefore, it is important to keep the inverter circuit output current and voltage in the same phase in the heating process in order to achieve soft switching. To solve this problem, it is possible to control the resonant inverter using the phase locked loop (PLL) method [8, 9].
There are many control methods used in the control of inverters such as pulse-width modulation (PWM), phase-shift, frequency and duty ratio. Because of the hard switching condition, switching losses increase in these control methods. Increased switching losses reduce the efficiency of the inverter while limiting the operating frequency. The low operating frequency causes the size increase of the passive elements used in the circuit, which increases the size and weight of the circuit. In addition, the size increase of the circuit elements will increase the costs [10, 11]. Soft switching technique can be used to solve these problems. Soft switching technique is provided by the inductor and capacitor added to the inverter circuit, and the type of inverter obtained is called as the resonant inverter. It is important to determine the appropriate control method in resonant inverter circuits. By means of the determined control method, switching losses can be reduced and operating frequency can be increased by providing soft switching [12, 13].

Pulse density modulation (PDM) control method used in resonant power converters provides power control in wide range and is used in different fields such as speed control of brushless DC motor [14], X-ray generators [15], wireless power transfer system [11], IH system [16], and inductively coupled power transfer system [17]. The output power value required by PDM control is realised gradually by omitting control pulses of the inverter which operates at resonant frequency. PDM control reduces switching losses by providing zero current switching (ZCS) if the inverter operates at resonant frequency [18–20].

Although many studies are conducted using PDM control technique, in this study, comparison of regular and irregular PDM-controlled MPPT is examined for IH system. The series resonant inverter control, which transfers the energy of the PV panels used in the system to stainless steel material, was realised with a new method, PDM-controlled MPPT. In the study, regular and irregular 32 PDM patterns were compared for IH application. The advantages and disadvantages of the regular and irregular PDM pattern length were presented. PLL technique was used to operate the system under ZCS condition continuously by locking the system at resonant frequency due to solar irradiation changes. The power control was provided by omitting control signals without changing the switching frequency according to the power values of PV panels in different solar irradiation conditions. In the system, the P&O algorithm was preferred as the MPPT algorithm since it has high efficiency. Total PV panel power of the system was 180 W and resonant frequency was determined as 38.5 kHz.

The sections of the study are as follows: after the introduction section, the structure of the series resonant inverter circuit is presented in Section 2. In addition, switching stages of the circuit according to PDM control method and PLL structure are examined in this section. Section 3 describes regular and irregular 32 PDM control patterns. In Section 4, the proposed PDM controlled MPPT algorithm is described. Section 5 presents the experimental results for regular and irregular 32 PDM control patterns. Finally, in the conclusion, Section 6, the advantages and disadvantages obtained as a result of regular and irregular PDM control patterns are determined by examining the results.

### 2.1 Full-bridge series resonant inverter

IH is the heating of the workpiece in the alternating electromagnetic field due to energy losses. IH technique is frequently used in industrial applications since it is appropriate for fast production and provides heating with high efficiency. High frequency DC–AC power converter is required to heat the workpiece [21, 22]. Figure 1 presents the full-bridge series resonant inverter circuit for IH.

Full-bridge inverter circuit consists of four power switches (Q1, Q2, Q3 and Q4), resonant capacitor (Cr), high frequency (HF) transformer, induction coil (Lp) and work piece (Rp). HF transformer was used in the circuit to allow higher current to pass through the workpiece.

In order to analyse the resonant inverter circuit, the simplified equivalent circuit must be obtained. Figure 2 shows the equivalent circuit.
The fundamental equations used in the analysis of the equivalent circuit are given below:

\[ R_{AC} = \left( \frac{r_1}{r_2} \right)^2 R_{eq} \]  

(1)

\[ f_r = \frac{1}{2\pi \sqrt{L_C R_C}} \]  

(2)

\[ Q = \frac{Q_f L_r}{R_{AC}} \]  

(3)

where \( R_{ac} \) is effective resistor and \( Q \) is quality factor [19, 23].

### 2.2 Switching stages of the circuit

Although PDM-controlled inverters have fixed operating frequency and fixed input voltage, the inverter is operated at three different switching states for adjusting the output power. In case 1, Q1 and Q4 switches are in conduction. The positive terminal of the DC source is connected to the node ‘a’. In this condition, resonant current flows through the resonant elements from left to right and resonant current exits from node ‘b’. In case 2, \( V_{ab} \) voltage is positive. In case 2, Q2 and Q3 switches are in conduction. The positive terminal of the DC source is connected to the node ‘b’. In this condition, resonant current flows through right to left and resonant current exits from node ‘a’. In case 3, \( V_{ab} \) voltage is negative. In case 3, input current is zero (\( V_{ab} = 0 \)) and up side or low side switches are in conduction. In both directions (from left to right and from right to left), resonant current flows. The resonant current circulates through the body diodes of switches. In case 3, the energy stored by the resonant elements is discharged from the effective resistor. Therefore, the current is in the form of damped oscillation. The damping oscillation of the current depends on the selection of the quality factor sufficiently high [10, 19, 20].

### 2.3 PLL structure

PLL control technique provides the detection of the zero transitions of the current signal on the series arm resonant circuit, and the system is locked at the resonant frequency, which provides the tracking of resonant frequency quickly. In this way, zero transition points are detected in the resonant frequency and ZCS condition is provided. The PLL structure is given in Figure 3.

When the PLL control technique is not used in the system, PDM control and ZCS cannot be achieved since the resonant frequency cannot be tracked. Therefore, PLL control technique should be used in order to track resonant frequency in the system. The PLL circuit is the circuit where the resonant current (\( i_r \)) and the inverter output voltage (\( V_{ab} \)) phase are locked. The PLL circuit consists of three parts. The first part is phase detector, the second part is low pass filter (LPF) and the last part is voltage-controlled oscillator (VCO), respectively. The operating logic of the PLL circuit is briefly as follows: In the phase detector the current signal phase and the VCO output signal phase are compared and an error signal is obtained. The error signal obtained from the phase detector is passed through the filter and applied to the VCO in the last part. If the frequency of the current signal and the frequency of the signal obtained from the VCO output are equal, the phase difference is zero, that is, locking at the specified frequency is performed. VCO output signal, the last part of the PLL circuit, and the triangular generator are compared by a comparator to obtain PWM pulses. The PWM signal obtained by the PLL circuit forms the input signal of the PDM control circuit [10, 24].

In analogue PLL techniques such as CD4046, frequency detection is performed at narrow ranges. Therefore, in this study, the system was locked at resonant frequency by providing frequency detection at a wider range using digital PLL technique [9, 25].

### 3 REGULAR AND IRREGULAR PDM CONTROL PATTERNS

The PDM control technique is a series of commands and is divided into two groups as regular and irregular according to the pattern length of control pulses within the period. In regular PDM control technique, the control pulses are distributed in a regular order and the distribution of the pulses is simple. In irregular PDM control technique, the control pulses are in an irregular order, but the current is evenly distributed within the period. The PDM pattern length theoretically can be 4, 8, 16, 32, 64, 128 \( \ldots \) \( 2^n \) [26, 27]. In this study, the comparison of regular and irregular 32 PDM patterns was conducted for PDM-controlled MPPT system; and the obtained advantages and disadvantages were presented.

#### 3.1 Regular 32 PDM control pattern

In order to obtain the switching signals of the circuit, the regular 32 PDM control table is written into the Arduino software. The
TABLE 1

| PD ratio | Regular PDM pattern |
|----------|---------------------|
| 1/32     | 10000000 00000000 00000000 00000000 |
| 2/32     | 11000000 00000000 00000000 00000000 |
| 3/32     | 11100000 00000000 00000000 00000000 |
| 4/32     | 11110000 00000000 00000000 00000000 |
| 5/32     | 11111000 00000000 00000000 00000000 |
| 6/32     | 11111100 00000000 00000000 00000000 |
| 7/32     | 11111110 00000000 00000000 00000000 |
| 8/32     | 11111111 00000000 00000000 00000000 |
| 9/32     | 11111111 10000000 00000000 00000000 |
| 10/32    | 11111111 11000000 00000000 00000000 |
| 11/32    | 11111111 11100000 00000000 00000000 |
| 12/32    | 11111111 11110000 00000000 00000000 |
| 13/32    | 11111111 11111000 00000000 00000000 |
| 14/32    | 11111111 11111100 00000000 00000000 |
| 15/32    | 11111111 11111110 00000000 00000000 |
| 16/32    | 11111111 11111111 00000000 00000000 |
| 17/32    | 11111111 11111111 10000000 00000000 |
| 18/32    | 11111111 11111111 11000000 00000000 |
| 19/32    | 11111111 11111111 11100000 00000000 |
| 20/32    | 11111111 11111111 11110000 00000000 |
| 21/32    | 11111111 11111111 11111000 00000000 |
| 22/32    | 11111111 11111111 11111100 00000000 |
| 23/32    | 11111111 11111111 11111110 00000000 |
| 24/32    | 11111111 11111111 11111111 00000000 |
| 25/32    | 11111111 11111111 11111111 10000000 |
| 26/32    | 11111111 11111111 11111111 11000000 |
| 27/32    | 11111111 11111111 11111111 11100000 |
| 28/32    | 11111111 11111111 11111111 11110000 |
| 29/32    | 11111111 11111111 11111111 11111000 |
| 30/32    | 11111111 11111111 11111111 11111100 |
| 31/32    | 11111111 11111111 11111111 11111110 |
| 32/32    | 11111111 11111111 11111111 11111111 |

The control pulses obtained according to the prepared regular PDM table are given in Figure 4.

As can be seen from Table 1, the software is simple as the control pulses are distributed sequentially during the period of 32 PDM controls. PDM logic design was developed in order to obtain regular PDM control pulses in Figure 4. In PDM logic design, frequency divider and parallel input serial output (PISO) shift register were used. PDM signals were generated in the system according to the MPPT algorithm. PDM signals prepared as a table (written in series) with the MPPT algorithm enter the inputs of D type flip-flops (FFs) in parallel. The data on the serial output is the PDM signal of the circuit’s upper switch (Q1) on one leg. The signal of the upper switch is passed through the NOT logic gate and the signal of the lower switch (Q2) is obtained from its output. The circuit operates synchronously since the clock pulse inputs of the FFs are connected in parallel in order to obtain serial data. The PDM signals required for the upper (Q3) and lower (Q4) switches of the circuit were obtained using D type FF and NOT logic gate. The designed 32 PDM logic circuit was used for both regular and irregular PDM control and is shown in Figure 5.

Although the software of the regular PDM pattern is simple, the number of elements used in the designed logic circuit does not change as the length of the PDM pattern is 32 in both regular and irregular PDM control in the study. Therefore, increasing the PDM pattern length complicates the software and also makes the logic design complicated.

3.2 Irregular 32 PDM control pattern

In order to obtain the switching signals of the circuit, the 32 irregular PDM control table is written into the Arduino software. The 32 irregular PDM pattern table prepared is shown in Table 2.

The control pulses obtained according to the prepared irregular PDM table are given in Figure 6.

In the irregular PDM control technique, the current is distributed evenly within the period and the damping current does not decrease to zero until the next period. However, its software is complicated.

4 PDM-CONTROLLED MPPT ALGORITHM

Block scheme of the proposed PDM-controlled P&O MPPT algorithm for IH system is shown in Figure 7.

The change of pulse density depends on the MPPT algorithm. The MPPT algorithm is the algorithm that creates the
maximum power that can be extracted from the PV panels depending on the solar irradiation amount and temperature. Control pulses decrease as the amount of solar irradiation falling on the PV panels decreases in the system. PDM-controlled P&O MPPT algorithm flowchart is given in Figure 8.

Initially, the current and voltage of the PV panel are measured and the power value is calculated and the pulse density (PD) is increased. The measured power and voltage values are compared with the previous values. If the power and voltage increases or decreases, the PD continues to increase. If either power or voltage decreases or increases, then the PD is decreased and the maximum power point is tracked. The maximum power obtained is transferred to stainless steel, which is the workpiece in IH.

5 | EXPERIMENTAL RESULTS

In the study, experimental studies were conducted for the IH application of regular and irregular PDM pattern in the PDM-controlled MPPT system. The advantages and disadvantages were determined by comparing the regular and irregular PDM patterns. Moreover, MPPT efficiency of the system was investigated. A PV simulator was used in the experimental study to test the PDM controlled P&O MPPT algorithm and solar irradiation level was rapidly changed step by step as 250–500–750 and 1000 W/m². To compare the two PDM control techniques 180 W prototype PV system was implemented with 60 W panels for IH system. Electrical specifications of the polycrystalline PV panel were entered as input data in the PV simulator and they are given in Table 3. The circuit parameters of the system and the circuit elements used are given in Table 4.

The hardware prototype of PDM-controlled IH system is shown in Figure 9.

5.1 | Experimental results for regular PDM

The power tracking of the P&O MPPT algorithm with regular 32 PDM control pattern was tested at different solar irradiation values. Figure 10 presents the MPPT efficiency testing at 250 W/m².

With the PV simulator interface, it is possible to observe whether the system is in MPP and the dynamic structure of the MPPT algorithm. MPPT efficiency ($\eta_{MPPT}$) was 99.23% at 250 W/m² solar irradiation. ZCS conditions in this irradiation value are given in Figure 11.

To extract maximum power from PV panels at solar irradiation at 250 W/m², it was found that the PD ratio should be 16/32. As it can be seen from Figure 11, 16 control pulses were omitted in accordance with the power value required by the PV panel and panels were operated in MPP. In addition, the ZCS conditions were achieved. However, it is seen that the peak value of the resonant current is high and the current decreases to zero. At the same time, voltage stresses occur. This indicates that magnitude of harmonics are large. In addition, voltage stresses cause the use of power switches and resonant capacitor with larger values in the circuit. This increases the cost and size of the circuit. Figure 12 presents the MPPT efficiency testing at 500 W/m².

MPPT efficiency was found as 99.59% at 500 W/m² solar irradiation. The regular PDM pattern in this irradiation value is shown in Figure 13.

The PD ratio was found to be 22/32 to extract maximum power from PV panels at solar irradiation at 500 W/m². As it
TABLE 2  Irregular 32 PDM pattern

| PD ratio | Irregular PDM pattern |
|----------|-----------------------|
| 1/32     | 10000000 00000000 00000000 00000000 |
| 2/32     | 10000000 00000000 10000000 00000000 |
| 3/32     | 00001000 10000000 00001000 00000000 |
| 4/32     | 10001000 10001000 10001000 10001000 |
| 5/32     | 00001000 10000000 10001000 00001000 |
| 6/32     | 10001000 10000000 10001000 10000000 |
| 7/32     | 10001000 10001000 10001000 10000000 |
| 8/32     | 10001000 10001010 10001000 00001000 |
| 9/32     | 10001000 10001010 00100010 00101000 |
| 10/32    | 10100010 10001000 10100010 10001000 |
| 11/32    | 10101000 10100010 10001010 00101000 |
| 12/32    | 10101000 10101000 10101000 10101000 |
| 13/32    | 10101010 00101010 10100010 10101000 |
| 14/32    | 10101010 10101000 10101010 10101000 |
| 15/32    | 10101010 10101010 10101010 10101010 |
| 16/32    | 11011100 10101010 10101010 10101010 |
| 17/32    | 11011100 10101010 11011100 10101010 |
| 18/32    | 11011100 10101010 11011100 10101010 |
| 19/32    | 11011100 10101010 11011100 10101010 |
| 20/32    | 11011100 10101010 11011100 10101010 |
| 21/32    | 01011110 11011100 11011110 01111110 |
| 22/32    | 11011110 11011110 11011110 11011110 |
| 23/32    | 11011110 11011110 11011110 11011110 |
| 24/32    | 11011110 11011110 11011110 11011110 |
| 25/32    | 11011110 11011110 11011110 11011110 |
| 26/32    | 11101110 11101110 11101110 11101110 |
| 27/32    | 11101110 11101110 11101110 11101110 |
| 28/32    | 11101110 11101110 11101110 11101110 |
| 29/32    | 11101110 11101110 11101110 11101110 |
| 30/32    | 11101110 11101110 11101110 11101110 |
| 31/32    | 11101110 11101110 11101110 11101110 |
| 32/32    | 11101110 11101110 11101110 11101110 |

...can be seen from Figure 13, 10 control pulses were omitted in accordance with the power value required by the PV panel and panels were operated in MPP. However, it is seen that voltage stresses are high again. Figure 14 presents the MPPT efficiency testing at 750 W/m².

MPPT efficiency was found as 99.82% at 750 W/m² solar irradiation. The regular PDM pattern in this irradiation value is shown in Figure 15.

To extract maximum power from PV panels at solar irradiation at 750 W/m², it was found that the PD ratio should be 29/32. As it can be seen from Figure 15, three control pulses were omitted in accordance with the power value required by the PV panel and panels were operated in MPP. It is seen that voltage stresses are high.

Figure 16 presents the MPPT efficiency testing at 1000 W/m².

MPPT efficiency was found as 99.92% at 1000 W/m² solar irradiation. The results of this irradiation value are found to be same for both regular and irregular PDM patterns, and the PDM pattern is given in Figure 17.

The PD ratio is 32/32 at 1000 W/m² solar irradiation value. Although there is no omitted control pulse in this irradiation value, it is seen that voltage stress does not occur.

As seen from the experimental results, ZCS is achieved for all power levels so theoretical switching power loss is zero. At maximum output power, conduction loss ($P_{con}$) of the IRFP260 MOSFET in implemented system is obtained as 0.36 W from...
FIGURE 8  Flowchart of the PDM-controlled P&O MPPT algorithm for IH

TABLE 3  Specifications of the polycrystalline PV panel

| Parameters                  | Symbol | Values |
|-----------------------------|--------|--------|
| Maximum power               | $P_{\text{max}}$ | 60 W   |
| Voltage at maximum power    | $V_{\text{MPPP}}$ | 17.6 V |
| Current at maximum power    | $I_{\text{MPPP}}$ | 3.41 A |
| Open circuit voltage        | $V_{\text{oc}}$ | 21.8 V |
| Short circuit current       | $I_{\text{sc}}$ | 3.81 A |

measured switch current by using Equation (4) [28]:

$$P_{\text{con}} = I^2 D R_{\text{DS(on)}}$$  (4)

5.2 Experimental results for irregular PDM

The power tracking of the P&O MPPT algorithm with 32 irregular PDM control pattern was tested at different solar irradiation values. Figure 18 presents the MPPT efficiency testing at 250 W/m².

MPPT efficiency was found as 99.84% at 250 W/m² solar irradiation. The irregular PDM pattern in this irradiation value is shown in Figure 19.

The PD ratio was adjusted as 19/32 to receive maximum output power from the PV panels in 250 W/m². As can be seen in Figure 19, MPP could be achieved when 13 control pulses were omitted based on the power needed by the PV panels. In addition, the ZCS conditions were achieved. Compared with the regular PDM pattern the peak value of the resonant current is not high, and the current does not decrease to zero. At the same time, it is seen that the voltage stresses do not occur. This shows that magnitude of harmonics is not large.

Figure 20 presents the MPPT efficiency testing at 500 W/m². As can be seen from the figure, MPPT tracking efficiency of 99.44% was obtained. Figure 21 presents the oscilloscope images of the control signal of switch, $V_{ab}$ voltage and resonant current for 500 W/m² solar irradiation.

The PD ratio was adjusted as 24/32 to receive maximum output power from the PV panels in 500 W/m². As can be seen from the figure, MPPT tracking efficiency of 99.44% was obtained. Figure 21 presents the oscilloscope images of the control signal of switch, $V_{ab}$ voltage and resonant current for 500 W/m² solar irradiation.

The PD ratio was adjusted as 24/32 to receive maximum output power from the PV panels in 500 W/m². For this situation, MPP was achieved when eight control pulses were omitted depending on the power requirements of PV panel.

TABLE 4  The circuit parameters and elements of the system

| Parameters/elements     | Symbol | Values/type |
|-------------------------|--------|-------------|
| Resonant inductor       | $L_r$  | 375 $\mu$H  |
| Resonant capacitor      | $C_r$  | 44.8 nF     |
| Effective resistor      | $R_{\text{ac}}$ | 11.7 $\Omega$ |
| Resonant frequency      | $f_r$  | 38.5 kHz    |
| HF transformer ratio    | $n_1:n_2$ | 25:1         |
| Power switches          | $Q_1, Q_2, Q_3, Q_4$ | IRFP 260N $R_{\text{DS(on)}} = 0.04 \Omega$ |

FIGURE 9  The hardware prototype of PDM-controlled IH system

FIGURE 10  The MPPT efficiency testing at 250 W/m² for regular PDM pattern
Figure 22 presents the MPPT efficiency testing at 750 W/m². As seen, the MPPT efficiency was found as 99.53%. Figure 23 presents the oscilloscope images of the control signal of switch, $V_{ab}$ voltage and resonant current for 750 W/m² solar irradiation.

The PD ratio was adjusted as 28/32 to receive maximum output power from the PV panels in 750 W/m² solar irradiation. For this situation, MPP was achieved when four control pulses were omitted depending on the power requirements of PV panel.

5.3 Comparison of regular and irregular PDM algorithms

As can be seen from experimental results, both regular and irregular PDM patterns have high MPPT efficiency (≥99%) and above) and ZCS conditions are achieved. However, software of regular PDM pattern is simple compare to irregular. On the other hand, in irregular PDM pattern, the peak value of resonant current is lower than regular PDM pattern, but it does not decrease to zero. In addition, voltage stresses are lower in the
irregular PDM pattern. This indicates that the amplitude of harmonics is small. Low voltage stresses ensure the values of the elements used in the circuit to be low, which significantly affects the cost and size of the circuit. Advantages and disadvantages obtained as a result of regular and irregular PDM patterns are given in Table 5.

The obtained findings show that 32 PDM regular or irregular pattern does not affect MPPT efficiency in IH systems. Regular MPPT is more advantageous in terms of software and hardware applicability. However, switches with high capacity are required due to switching stresses. The inverter efficiency of the system was found to be above 97%.

6 | CONCLUSION

In this study, the energy extracted from PV panels was transferred to stainless steel and IH was realised. In the study, the effect of P&O MPPT algorithm with regular and irregular PDM control pattern, on the series resonant inverter was investigated.
The advantages and disadvantages of the regular and irregular 32 PDM pattern on the system were analysed experimentally. A PV simulator was used to examine the MPPT efficiency in the system, and the series resonant inverter was adjusted at a frequency of 38.5 kHz. The total PV panel power was 180 W and this study is appropriate for medical applications, which require low power. In order to analyse the regular and irregular PDM control patterns, the solar irradiation level was changed to 250–500–750 and 1000 W/m². According to the analysis results, 99% and above high MPPT efficiency was obtained in both PDM patterns. At the same time, ZCS conditions were provided in all rapidly changing solar irradiation values. In order to provide ZCS conditions, zero crossing points of the current were detected by using PLL control technique in the circuit. By doing so, the restricted operating frequency is increased and hard switching conditions, which constitute the main challenges of the traditional PWM switched MPPTs, are overcome. However, control algorithm software of the irregular is more complex than regular, but the main disadvantage of the irregular PDM pattern is that it has a complex software structure. The most important advantages are that the peak values of the current and voltage stresses in the irregular controlled circuit
FIGURE 23 750 W/m², control signal (CH2), V_ab voltage (CH1) and resonant current (CH4)

TABLE 5 The comparison of regular and irregular PDM patterns

| PDM pattern | Logic control circuit | Software | η_MPP | Current/voltage stress | Cost | Size |
|-------------|-----------------------|----------|-------|------------------------|------|------|
| Regular     | Simple                | Simple   | HIGH  | Large                  | High | Large|
| Irregular   | Complex               | Complex  | HIGH  | Small                  | Low  | Small|

are not high. This ensures that the power switches and resonant capacitor values in the circuit are low, which affects the cost, size and weight of the system.

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