Design and Implementation of Portable Auto Defibrillator

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Abstract. Sudden Cardiac Arrest (SCA) is a case that made the heart stop pumping the blood. Ventricular fibrillation (VF) and ventricular tachycardia (VT) are the major causes that lead to cardiac arrest. To treat SCA, a defibrillator device is used to return the heart to its normal sinus rhythm. The main generation of the defibrillator is the manual type which has many limitations. It requires the physician’s instruction to determine the patient state and the amount of joule required; therefore, it is preferable to design an auto defibrillator. The aim of this paper is to design a hardware implementation system of auto dc-shock utilized in the emergency case for diagnosing patient case and recovering the normal state of the heart. This prototype consists of five main parts, including the diagnosing system, high voltage section, charging unit, discharging unit, and safety unit. The output of diagnosing system is followed by charging and discharging period in order to get a suitable amount of joule according to patient situation of 50, 100, 120, and 150 joule discharged on the patient body by using a biphasic system provided by safety mode circuit so that the discharge process automatically happens in the case of not discharged on the patient body. The proposed diagnosing system in hardware design was tested on several patients in Ibn al-Nafis hospital and healthy patients at home and the accuracy was achieved of 97.03%, specificity is 97.8%, and the detection error rate is 3.09%.

Keywords: Auto Defibrillator, charging unit, discharge unit, ECG, safety unit.

1. Introduction

Defibrillation is a process for reconquest normal sinus rhythm (NSR). The main task of the defibrillator is to deliver a high electric shock for the heart through the thorax wall. The electric shock requires a large amount of voltage and joule in order to reconquest the heart to Normal Sinus Rhythm (NSR) [1]. The basic kind of electric shock is in the form of monophasic wave and biphasic wave. In monophasic, the current direction in one side means the heart take the current in one direction which is suitable to return to NSR. In biphasic, the electrical current in two directions with lower and lighter energy as compared with the monophasic type and this makes reducing the damage of battery that leads to less damage on the heart. Biphasic waveform has another advantage of minimizing the weight and size of an AED [2]. The method of delivering a shock to patients is by two-way manual method and auto method.

The previous researcher has reviewed in manual and auto defibrillator design. Wenguang Han. et al., 2010 [1] designed portable AED with the aid of Samsung S3C2440 that has a processor of 16/32 bit with the low power unit in order to make analysis to get a suitable selection of energy level. The experimental result was obtained by the new algorithm is 69.1 for sensitivity and the
accuracy is 88.7%. Ferry Pratamal, 2011 [3] designed a manual defibrillator system with microcontroller AT89CSI and the design includes a circuit for selecting the energy provided signal from microcontroller and from capacitor charging and discharging unit also includes paddles for receiving the electric shock. The author can get energy selection values of 10, 15, 20, 25, and 30 joules appeared on display. A study by Vignesh et al. [4] developed the defibrillator system and made it auto design that relay on PIC16F877. The microcontroller is supplied by a signal from the sensor of beat rate to generate PWM signal for the defibrillator system. The researcher used the Bluetooth technique and android system to get telemedicine monitoring system. The result that researcher got is to determine the case of the patient by display unit but cannot determine the amount of joule for each patient condition. Jacopo, 2017 [5] proposed to design open source for AED that consists of two main sections electric unit that involve HV and H-bridge. High voltage (HV) circuit that charging the capacitor using ringing choke converter followed by PWM to make the switch on control unit which is an important part of prototype design represented by programing cypress poss chip and contains ARM cortex M3-CPU for analysis ECG signal that is required in defibrillation. The result of design 1700volt with sensitivity of more than 95% for recognition.

In this paper, the proposed design is auto dc shock system that consist of diagnosing system and high voltage section system. In the diagnosing system, the microcontroller determines the pathological case of a patient with considering the charging and discharging time to get suitable voltage from charging flyback converter.

2. Material and Methods

It involves many goals include design of diagnosing system which is represented by microcontroller system to determine patient situation. Second stage is giving an order to defibrillator system about patient situation require energy shock. Third stage applies a suitable voltage by designing DC-DC converter and get amount of joule relies on the charging and discharging intervals. The block diagram of hardware design is expressed in figure 1

![Figure 1. Block diagram of hardware design.](image)

2.1. Diagnosing System

This is the first stage of design based on taken signal from the patient’s body and display the situation of this patient. This process involves three main parts:

2.1.1. Microcontroller

Arduino is the basic part of the diagnosing system and it is responsible for all auto process happened in dc –shock system design. This microcontroller based on control the process which involves patient situation, charging time safety circuit and discharging time. Type of Arduino used in the proposed design is Arduino Uno which considers the main part of a circuit which is represented by microcontroller board that relies on the ATmega 328 [6] (see App.A).
2.1.2. Biomedical Sensor
In the proposed diagnosing system, heart pulse sensor is utilized to measure the Beats of heart relies on optical power at scattering and absorption of light that has occurred during its course in the blood with changing in a heartbeat.

2.1.3. Display Unit
This unit is responsible for indicating patient status by showing heart signal and heart rate. The screen that was used is Oled type represents an acronym for organic-light emitting diode characterized by 128×64 display in 0.96-inch size.

2.1.4. Connection of Diagnose System
The connection of the diagnosing system is expressed in Figure 2.

![Figure 2. Connection of the diagnosing system](image)

2.2. High Voltage Section
2.2.1 Design of Transformer
The first main section of charging unit is represented by step-up transformer LG MS-192A with maximum power that bears of 1200 watt. It was used for raising the voltage from low to high voltage. The transformer output is three-fold input according to the transformation ratio of 1:3 and reaches to 933 volts. The equations 1 and 2 express primaries and RMS values [8]:

\[ v_{\text{rms}} = \frac{v_{\text{max}}}{\sqrt{2}} \]  
\[ v_{pri} = \sqrt{2} \times v_{\text{rms}} \]  
\[ v_{\text{max}} = 220 \times \sqrt{2} = 313 \text{ volt} \]  
\[ v_{\text{sec}} = 3 \times 313 = 933 \text{ volt} \]
2.2.2 Bridge Rectifier
Converting AC input voltage to DC voltage to charge the capacitor with DC voltage. Four diodes are connected as bridge design circuit. The type of diodes used is CL01-12 for higher voltage tolerance up to 12 kV.

2.2.3. Flyback Converter Design
DC to DC converter represents a circuit that electronically designed in a form can convert the dc power to another level form of voltage this can achieve by controlling output voltage by PWM signals of device gate [9]. The magnetic material of the transformer with ferrite core works at high-frequency power electronic device such as SMPS. The type of ferrite core used in the design is manganese zinc (MnZn) that has higher permeability and use less than 2MHz frequency. The reasons for using ferrite core are to prevent eddy current and hysteresis losses [10].
In the proposed design, Flyback converter is used for high voltage application. In charging unit of auto DC-shock we Flyback converter was designed to rise up the voltage of charging the capacitor. The maximum rising voltage of DC-DC converter is 1981.7 volt
In practical design, Two MOSFETs type IRF740B were used with parallel connection to bear high voltage up to 400 volts to control the amount of duty cycle used for operating flyback converter. The MOSFET with a charging relay takes the order from the microcontroller to control the period of charging according to patient status.

2.3. Charging Unit
The period of delay that is found in most of the electronic devices and electric circuit design are represented by time delay and delay relies on the active ingredients in the design of circuit which is performed capacitor, resistance or inductive. so, this delay of time is called τ.
RC circuit of charging unit in defibrillator determines the time of charging the capacitor. To compute the time of the charging unit, apply the equation 3 for charging capacitor [11]:

\[
V_C = V_S (1 - e^{\frac{-S}{RC}}) \tag{3}
\]

where \(V_C\) is capacitor voltage, \(V_S\) is DC supply voltage and \(RC\) is the time constant of the circuit.

In practical design, charging unit consist of relay responsible for charging process according to microcontroller decision to determine the amount of period. The type of relay used in charging (QIANJI) JQX-96F relay for high power voltage. In practical design, resistance is connected in series with a relay to slow down the charging process. This resistance used can bear high watt and its value is 22 kΩ. The other part is capacitor as an essential component of electric shock device due to store a large amount of energy from the charging unit. The type of capacitor used in the design is Nippon Chemi electrolyte KMH and its value of 470 µF, maximum voltage for this capacitor is 450 V. Six capacitors in series are connected in the proposed design in order to get the total capacitor value = 78.33 µF

To compute amount of joule according to the proposed design, equation 4 can be applied as below:

\[
\text{Amount of joule} = \frac{1}{2}cv^2 \tag{4}
\]

where \(c\) represents capacitor value, \(v\) represents the voltage across capacitor

Amount of joule of the proposed design = \(\frac{1}{2} \times 78.33 \times 10^{-6} \times 1981.7^2\)
5

= 153.8 j , the required joule of device.

2.4. Discharge Unit and Biphasic System
It is a process that occurs after the capacitor is fully charged. The relationship between voltage and current with discharge time is the exact opposite in the charging process. The voltage of capacitor in discharge period expression can be calculated by equation 5 of discharging process [10]

\[ V_C = V_S e^{-\frac{t}{\tau}} \]  

where \( V_C \) is the capacitor voltage, \( t \) is discharge time, \( V_S \) is source voltage, and \( \tau \) is the delay time. In practical design, discharging into patient body currents across the biphasic system.

The biphasic system means the discharging in two directions programmed by Arduino software programing using four relays each two relays are connected together

2.5. Self-Advice-Electrode (Paddle)
This electrode is linked to the discharging unit if the patient needs shock and gives an order to deliver the electric shock to the patient. The type of paddle used in auto dc-shock is gel pads differs from that used in manual type, and it is suitable for people who are not trained.

2.6. Safety Mode Unit
The electric shock device requires high voltages to get the right amount of joules. In case of charging the capacitance to a certain voltage and the patient's condition does not require, an electric shock requires for the presence of a protection unit in the device in order to be discharged automatically, and the patient is protected. This unit involves relay with two resistances of 5.1k Ω each which take order directly from the microcontroller. The Automatic discharge needs a few seconds to be done. The type of relay and resistance used in the circuit is KACO RY16020L5 B. This unit is programmed according to the status of the patient. The schematic of the proposed design is shown in Figure 3.

![Figure 3. Schematic of the proposed design.](image)
3. Experiment Procedure

3.1. Experiment of Diagnosing System in the Hospital
A test was conducted on the diagnostic system and was applied to a group of patients ages of 50-70 years, including women and men in Ibn Al-Nafis Hospital within the cardiac resuscitation unit. Some of them are in a stable condition, and some are in a state of fainting, and some have rapid heart rate. The diagnostic system was linked to the patient by placing the patient's finger on the heart sensor. Readings were gotten on the screen used in the diagnostic system in which the heartbeat and the shape of the ECG signal are shown, and the pathological condition is diagnosed. The type of calibration monitor that used in the hospital is Nihon kohden life scope monitor to view different vital signs for the patient which involve respiratory rate, heart rate and blood pressure. The result obtained from the patient is shown in Figure 4.

![Figure 4](image)

**Figure 4.** The experimental results in hospital (a and b at healthy Case), (c and d at unhealthy case)

3.2. Experiment Procedure of Diagnose System at Home
The diagnose system is applied to group the healthy people among them men, women, and children of ages are different, and the system is tested and classify as healthy state. In this experiment, the reference-based on is blood pressure device type geratherm desktop which views high and low blood pressure with the heart rate of the patient. Figure 5 expresses diagnose system connected to healthy persons at home.
The algorithm of the diagnosed system is tested, and the results are the difference between the readings of the sensor in diagnosing system and blood pressure device applied to a group of people at home as shown in curve chart of Figure 6.

3.3. Experiment Procedure of High Voltage Section
This part of the practical experiments includes obtaining the required amount in two ways so that the capacitance is charged and the required voltages are obtained. This experiment involves getting suitable voltages and a suitable period of charging. It is tested by using voltmeter and timer by connecting a voltage divider circuit that divides the voltages in the step of 10, as shown in Figure 7. The charging unit calculation is expressed in table 1. The experiment results are summarised in Table 2. Figure 8 expresses the difference between calculation and experiment results.
Figure 7. The experimental result of the high voltage section.

Table 1. Calculation results of charging unit design

| Patient state       | Required joule | Voltage of capacitor | Time for charging capacitor |
|---------------------|----------------|-----------------------|-----------------------------|
| Atrial flutter      | 50 j           | 1129.88 v             | 0.844 \( \tau =1.45 \text{ sec} \) |
| Atrial fibrillation | 100 j          | 1601.28 v             | 1.65 \( \tau =2.83 \text{ sec} \) |
| Ventricular tachycardia | 120 j          | 1750.5 v              | 2.15 \( \tau =3.69 \text{ sec} \) |
| VF                  | 150 j          | 1957.02 v             | 4.4 \( \tau =7.5 \text{ sec} \) |

Table 2. The experimental results of high voltage section

| Patient state       | Required joule | The voltage of the capacitor in the experiment | Time for charging capacitor in the experiment |
|---------------------|----------------|-----------------------------------------------|---------------------------------------------|
| Atrial flutter      | 50 j           | 1160 v                                        | 1.45 sec                                    |
| Atrial fibrillation | 100 j          | 1660 v                                        | 2.89 sec                                    |
| Ventricular tachycardia | 120 j         | 1770 v                                        | 3.87 sec                                    |
| VF                  | 150 j          | 1980 v                                        | 7.67 sec                                    |
3.4. Validation Performance of Hardware

The evaluation of the system performance for smart dc-shock system design can be expressed in the validation of the diagnosing system. The diagnose system can be evaluated by sensitivity, specificity, and accuracy according to equations 6 till 9.

\[
\text{Accuracy} = \frac{TP + TN}{TN + FP + FN + TP} * 100\% \hspace{1cm} \text{6}
\]

\[
\text{Detection error rate (DER)} = \frac{FP + FN}{TP} * 100\% \hspace{1cm} \text{7}
\]

\[
\text{Sensitivity (se)} = \frac{TP}{TP + FN} * 100\% \hspace{1cm} \text{8}
\]

\[
\text{Specificity} = \frac{TN}{TN + FP} * 100\% \hspace{1cm} \text{9}
\]

where TP represents all cases which correctly detect the disease, T_N represents all healthy cases that do not have the disease, FN refers to abnormal cases that will give false diagnose, FP refers to all normal cases that are falsely detected.

The diagnose system will be applied to 100 pathological cases, including 20 cases in Ibn AL-Nafis hospital/cardiac resuscitation and other healthy people at home. For evaluation, there are two groups of disease and non-disease, as shown in Table 3.

| Disease     | Non- Disease                  |
|-------------|-------------------------------|
| True positive (TP) | False positive (FP)         |
| False negative (FN) | True negative (TN)        |

**Figure 8.** Calculation and experiment results.
The diagnose system algorithm was applied to 20 patients in the hospital, and 80 patients in the home and the accuracy was measured as 97.03%, specificity is 97.8%, the detection error rate is 3.09%, and sensitivity is 88.88%. As displayed in Table 4. Also, Figure 9 expresses the deference between the diagnosing monitor and calibration monitor in Ibn-AL-Nafis hospital.

Table 4. Validation of the diagnosing system

| Number of the total case | Number of cases in Ibn AL-Nafis hospital | Number of cases in the home |
|-------------------------|-----------------------------------------|-----------------------------|
| 100                     | 20                                      | 80                          |
| TP                      | 8                                       | 0                           |
| TN                      | 11                                      | 78                          |
| FN                      | 1                                       | 0                           |
| FP                      | 0                                       | 2                           |

Figure 9. Diagnosing system and calibration monitor in Ibn Al-Nafis hospital.

4. Results
The result of hardware design is expressed as a calculation result and experiment result. In calculations result, the maximum time required for the charging capacitor is 7.5 sec to get 150 joules. The amount of joule for each state of the patient relies on guidelines determined by the American Heart Association, and it is suitable for restarting normal patient state. Theoretical results of the charging circuit for the proposed design expressed in table 5 for four defibrillators required cases according to equations 3 and 4.
Table 5. Calculation results of charging unit design

| Patient state           | Required joule | Voltage of capacitor | Time for charging capacitor |
|-------------------------|----------------|----------------------|-----------------------------|
| Atrial flutter          | 50 j           | 1129.88 v            | 0.844 \( \tau = 1.45 \) sec |
| Atrial fibrillation     | 100 j          | 1601.28 v            | 1.65 \( \tau = 2.83 \) sec |
| Ventricular tachycardia | 120 j          | 1750.5 v             | 2.15 \( \tau = 3.69 \) sec |
| VF                      | 150 j          | 1957.02 v            | 4.4 \( \tau = 7.5 \) sec   |

As expressed in Figure 10, the relation between the amount of joule and time required for charging indirectly proportional as joule is increasing, the time of charging is increased.

![Figure 10. Chart of the calculation results.](image)

In the discharge unit and after completing charging, the capacitor to a certain level of voltage is based on the patient statement. Discharge process starts in order to recover the heart to a normal condition. Time of discharging differs from one state to another according to equation 5. Apply this equation for the different case of required joule 50, 100, 120, and 150 joules. The calculation results of the discharge unit are described in table 6. The experiment results are expressed in previous section 3.

Table 6. Calculation results of the discharge unit

| Patient state           | Required joule | Voltage of capacitor | Time for discharging capacitor |
|-------------------------|----------------|----------------------|--------------------------------|
| Atrial flutter          | 50 j           | 1129.88 v            | 0.96 sec                       |
| Atrial fibrillation     | 100 j          | 1601.28 v            | 0.366 sec                     |
| Ventricular tachycardia | 120 j          | 1750.5 v             | 0.21 sec                      |

The amount of joule and voltage are inversely proportional to the time of discharge as expressed in Figure 11.
Figure 11. The relation between discharge time and joule.

5. Conclusions

Designing prototype of auto dc-shock as a medical device is suitable for giving treatment for VF, VT, and Easy so this suitable diagnose system was proposed for untrained people and can handle by the medic. Two experiments were applied to the diagnostic system depending on a group of patient’s first experiment in Ibn Al-Nafees Hospital. The results of the diagnostic system were almost identical with the monitor attached to the patient's body as explained in section 3.1. The second experiment was applied to a group of people at home, and the results were almost identical as explained in section 3.2. Calculation results are almost identical with practical results. By hardware design, it was obtained sensitivity is 88.88%, specificity is 97.8%, accuracy is 97.03 and detection error rate is 3.09%. Low cost can be compared to other commercial types. Successful defibrillations depend on the delivery of the shock to a critical mass of myocardium depending on some parameters such as; transthoracic impedance, cellular response, defibrillation threshold, electrode size, quality of electrode surface, electrode paddles-skin interface, electrode paddle force, and electrodeposition.

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