DEVELOPMENT OF A CLOSED LOOP FUNCTIONAL ELECTRICAL STIMULATION

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ABSTRACT

Objectives

This report describe the development and technical details of a newly developed Functional Electrical Stimulation (**FES**) namely **FES2013** with a feedback system for psychophysiological study.

Materials and Methods

Seven pre-determined design criteria (DC1 – DC7) were introduced for the safety and research versatility of the FES. The important components of the proposed design are Arduino Uno as pattern generator, high voltage switch, and integration of voltage to current converter with Wilson current mirror as the driving stage.

Results

The flexible closed loop FES system was able to supply consistent 0 ~140mA pulsed current, pulse width of 50 ~ 500 micro second, pulse repetition rate of 50 ~ 100 Hz and functionally monophasic or biphasic pulses based on the preconfigured knowledge embedded in the feedback system. The skin model show that the FES2013 had below 0.3% tolerance as a result of the output current deviation. Theoretically, all the seven design criteria were met.

Conclusion

The FES2013 is ideally suited for research purposes due to the safe design, having the flexible closed loop operating condition capability, easy coding of Arduino Uno and cheaper than commercial FES system. The circuit and software coding details are provided.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

DC	Desired characteristic
DSP	Digital signal processor
EMG	Electromyography
FES	Functional electrical stimulation
NMES	Neuromuscular electrical stimulation
SCI	Spinal cord injury
SRM	Shift register Memory

Chapter 1. INTRODUCTION

1.1. Background

An injury to the spinal cord can cause loss of motor control as spinal cord does not have the ability to heal itself. Due to this injury, there is no path for the brain to transmit and receive signals from muscle below the level of the lesion thus usually resulting in a total or partially loss of sensory function and paralysis. For example, a lumbar spinal cord injury (L1 – L5) will result in no signal reach to the gluteus maximus muscle via the brain (i.e., motor cortex and cerebellum) and inferior gluteal nerve route as shown in Figure 1-1. A spinal cord injury (SCI) is a medical problem that affect ~12,000 patients in Australia and 400,000 people in North America. Currently, there is no SCI registry in Malaysia. But, the seriousness of this injury manifest from the 290 patients that admitted to the Department of Rehabilitation Medicine, Hospital Kuala Lumpur from 2006 to 2009 (Ibrahim et al., 2013).

In addition, the irreversibility of SCI provides secondary complication such as loss of muscle strength, pressure sores, osteoporosis in their paralysed limbs and unregulated visceral functions such as heart rate, body temperature and blood pressure (Lynch & Popovic, 2008). Over the past few year, several SCI medical sequel such as the renal and urinary tract complication that affect morbidity and mortality is tackle from improvement in medication and aseptic catheterization.

In long term, SCI patients are vulnerable to the risk of cardiovascular disease (Fornusek, Davis, Sinclair, & Milthorpe, 2004). Although increasing exercise and physical activity can help decreasing the risk of cardiovascular disease in SCI patients, their activity is limited to only upper body exercise such as arm cranking and wheelchair ergometer. Nonetheless, arm exercise does not provide enough cardiovascular training since it only utilise a smaller muscle mass that leg exercise. Beside, addition of arm cranking activity and wheelchair propulsion may lead injury of the upper limb joint due to overuse.

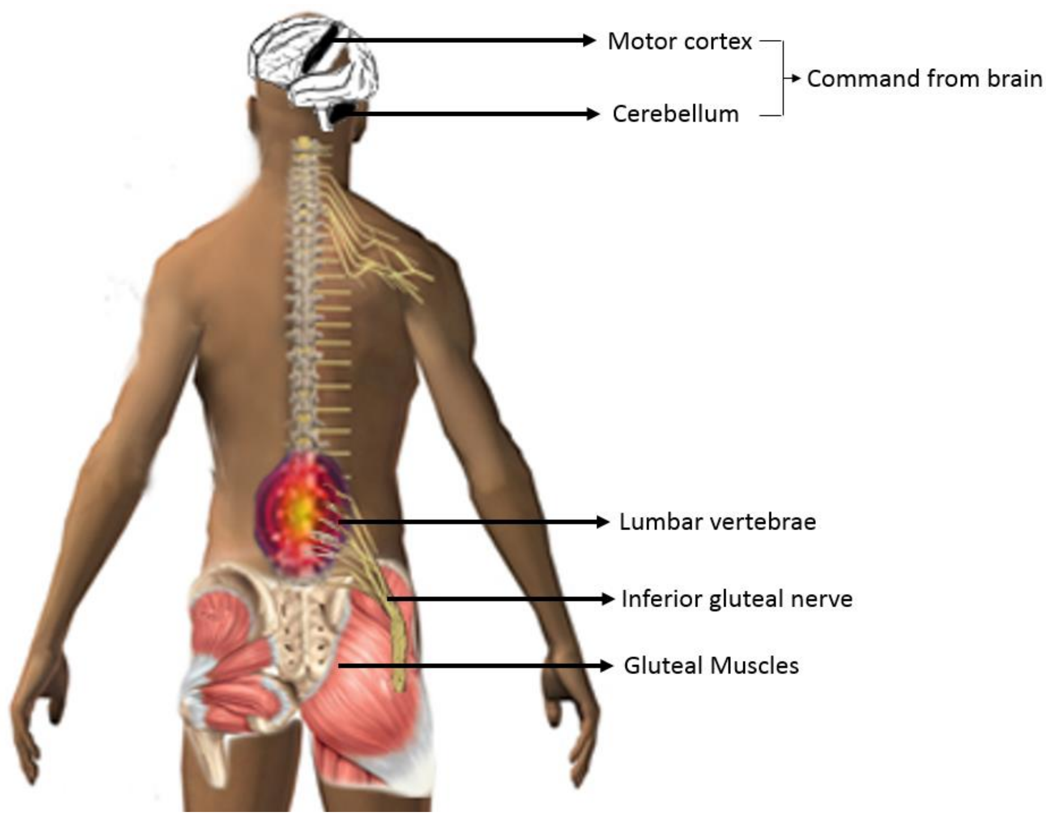


Figure 1-1 Lumbar level injuries result in paralysis of lower limb.

1.2. Functional electrical stimulation

Functional electrical stimulation (FES) is a methodology to elicit muscle fibres or nerve cell excitation in a coordinated sequence using a precisely controlled high voltage electrical pulse. Pioneered by Luigi Aloisio Galvani's observation, a dead frog's muscle twitch when struck by a spark in 1791 (Han-Chang, Shuenn-Tsong, & Te-Son, 2002). However, only in 1960s where FES evoked leg muscle contraction was first commercialized and used in clinical rehabilitation therapy to help paralyzed patient who suffer from spinal cord injury to do exercise (Hamzaid & Davis, 2009). Since then, many available FES that help patient to perform drop foot movement (Burridge, Swain, & Taylor, 1998), standing, walking (Klose et al., 1997) and asynchronous cycling (Fornusek et al., 2004).

By manipulating the FES exercise protocol, FES shows overwhelming outcome. FES cycling for different training period in the range of 13 weeks to 6 months period showed promising result such as control lost muscle (Baldi, Jackson, Moraille, & Mysiw, 1998), increase lower extremity blood flow (Nash, Montalvo, & Applegate, 1996), and increased in lower extremity muscle volume (Skold et al., 2002). To add to that, FES evoked leg muscle contraction in a single day shows resulting in significant increased venous return as well as better cardiovascular responses during submaximal exercise (Davis, Servedio, Glaser, Gupta, & Suryaprasad, 1990). The potential benefit of FES exercise in term of possible health and fitness were systematically reviewed and documented by (Hamzaid & Davis, 2009).

1.3. Muscle fatigue

Alas, FES exercise training suffer from the rapid muscle fatigue although it can provide many advantage as discussed in section 1.2. Muscle fatigue is defined as a condition where the subject does not have the ability to maintain the desired power output under the given intensity during neuromuscular electrical stimulation (NMES) exercise (MacIntosh & Shahi, 2011).

Compared to voluntary contraction, muscle fatigue degradation occur much faster during functional electrical stimulation contraction (Binder-Macleod & Snyder-Mackler, 1993; Kjaer et al., 1994). Electrical stimulation recruits fast twitch fibres which have low energy store. Contracting the fast twitch fibres at a much higher frequency could result in exhaustion of the muscles fibres and lead to higher rate of achieving fatigue (Allen, Kabbara, & Westerblad, 2002)

Fatigue is a direct result either from sensitivity degradation of the contractile protein to Ca^{2+} or lower free Ca^{2+} per stimulation (MacIntosh & Rassier, 2002). While other researcher (Allen et al., 2002; Barstow et al., 2000; McCully, Authier, Olive, & Clark, 2002) suspect that the metabolites (i.e., H2PO$_{4-}$, HPO4-2, H^+ and lactate) build up or lack of calcium store can decrease the force during excitation-contraction coupling.

1.4. Significance of the study

Since SCI patient losses of control and sensation in lower extremities, there is no sensory path to signal muscle fatigue development (Mizrahi, 1997). Since fatigue shows a progressive change in NMES performance, approach in modifying the neuromuscular system during exercise is essential (Kay et al., 2001). Previously, several researcher use electromyography (EMG) controlled FES for ankle dorsiflexion (Yeom & Chang, 2010) and cycling (C.-C. Chen, He, & Hsueh, 2011). While, other researcher (Dimitrijevic, Stokic, Wawro, & Wun, 1996) analysed the surface EMG of the arm muscles to determine effectiveness of mesh-glove afferent stimulation to motor control of voluntary wrist movement. Furthermore, Mizrahi suggested use of an EMG signal as muscle fatigue indicator (Mizrahi, 1997). These studies indicated the potential of embedding a fatigue detection system using EMG sensor to optimize an activity by delaying fatigue in a closed loop manner. Unfortunately, EMG received negative critic since its measurement is prone to motion artifact error, undesirable auxillary myoelectric content, quality of EMG signal collection dependent on electrode placements (Chang et al., 2012).

A control system can be used to regulate the stimulation parameters to increase the exercise length (Mizrahi, 1997). Due to that reason, researcher are looking for other alternative to find other muscular physiological feedback and metabolic quantities as an indicator for muscular fatigue Up to recently, various exploratory study had been conducted in looking for alternative feedback control such as muscle temperature, muscle movement and muscle vibration (Chang, Hamzaid, Khaidir, Termimi, & Hasnan, 2012). Furthermore, determining the optimal setting of FES device to compensate for fatigue also remains an active research field (Mizrahi, 1997; Velloso & Souza, 2007a)

In any exploratory study, researcher usually experiment various FES parameter setting (e.g., current intensity, frequency, width, and wave shape) as well as the best feedback parameter (e.g., muscle temperature, muscle movement and muscle vibration) to test their study hypothesis. This setup required a closed loop system to analyse the study protocol output from various sensor (e.g., temperature sensor, flexible bend sensor, vibration sensor).

Since the first FES in 1960s, there are many commercially available electrical stimulation system and each comes with improvement in design. Disappointingly, most of the system were not open architecture friendly since the designed system were developed specifically for clinical application (e.g., grasping, standing, and cycling). Thus, this study sought to design a new FES device that is specifically build to be used in any FES-exercise research related.

1.5. Objectives of the study

1) To develop a safe, flexible closed loop functional electrical stimulator with the ability to easily tune the pulse width, consistent pulse amplitude, frequency and duty cycle for FES psychophysiological study.
2) To test the efficacy of the closed loop FES in delivering precise constant current under varying load.

1.6. Outline of the report

This report divided into 4 sections. The first section will discuss in detail about the reason behind the importance of FES exercise, important parameter that considered when using FES as well as review on previous FES design. In the second section, reader will have the clear view about the study protocol. The expected result and discussion will be discussed in third section. Lastly, section four will summarize all the writing in this report.

1.7. Terminology

This report utilised few terminology that widely mention throughout the writing. The phrases are as define below.

Fatigue

A condition when the user unable to carry on with the exercise under the given intensity. Muscle contraction under electrical stimulation can be defined as “ a response that is less than the expected or anticipated contractile response, for a given stimulation” (MacIntosh & Rassier, 2002).

Functional Electrical stimulation (FES)

Application of external electrical stimulation on neuromuscular in a sequence and coordinated manner to perform functional task such as walking, cycling or standing (Fornusek et al., 2004)

Spinal cord injury (SCI)

Spinal cord injury is a medical term for spinal cord suffered from trauma. The level of SCI depends from the level of the spinal cord lesion and affect all the motor and sensory interconnection below (Fornusek et al., 2004).

Stimulation Parameters

Functional electrical system usually output a waveform that characterise by pulse amplitude (mA) and pulse width (μs), stimulation frequency (Hz), and duty cycle (%). Each of the parameter is define as, 1) pulse amplitude correspond to the height of the pulse, 2) pulse width correspond to length of the pulses, 3) stimulation frequency define as total pulse given per second during the stimulation and 4) duty cycle as the ratio of stimulation time to the total time under one complete stimulation cycle.

Chapter 2. LITERATURE REVIEW

2.1. Functional electrical stimulation of muscle

2.1.1. Physiology of neuromuscular electrical stimulation

In neuromuscular electrical stimulation (NMES), external potential difference across tissue is artificially created via two opposite charge extracellular electrode. The potential difference allow the injected external current to flow along axon. Muscle contraction only evoke when the current across axon is above certain threshold to depolarize its membrane and triggered action potential (Fornusek et al., 2004).

2.1.2. Stimulation pulses

In one cycle of NMES, the stimulation is divided into continuous constant pulses of current and finite periods of "electrical silence" (Baker, Wederich, McNeal, Newsam, & Waters, 2000; Simcox et al., 2004) as shown in. The continuous pulse are characterize into duration of applied current into the muscle (i.e. pulse width), the maximum current of the applied current (i.e., pulse amplitude), the shape of the pulse (e.g., rectangle, square, triangle), and number of phases to the pulse (e.g., biphasic and monophasic) as shown in Figure 2-1.

The ratio between continuous constant pulses of current and electrical silence known as duty cycle. Stimulation frequency define as cumulative pulse introduce per second during the stimulation. For example, the waveform for FES parameters with the following setup (frequency; 100Hz, Duty cycle; 50%, pulse width; 50 µs, pulse amplitude; 140 mA) for training regime of 2 seconds as shown in Figure 2-1.

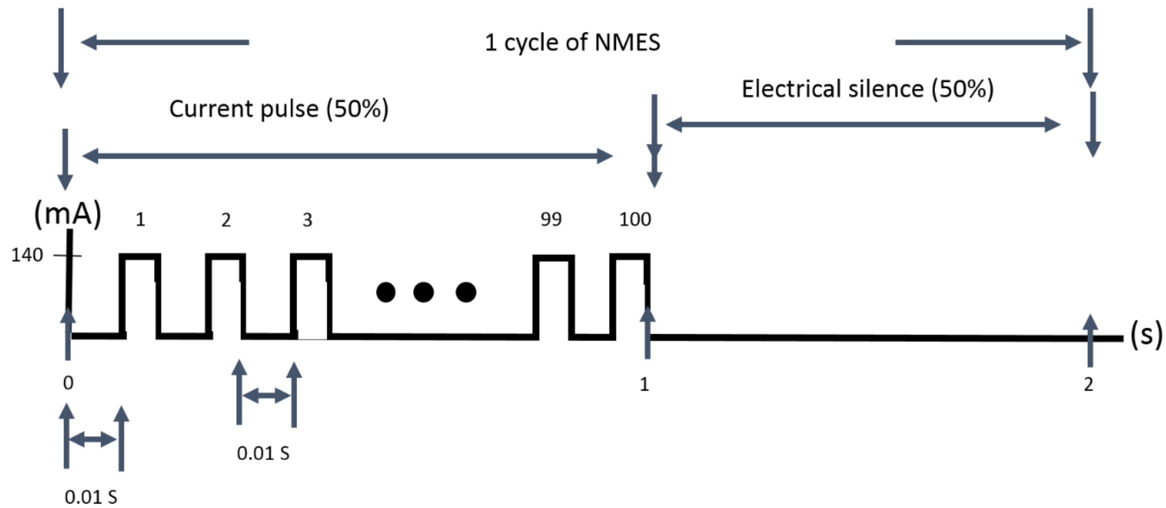


Figure 2-1 The FES parameters with the following setup (frequency; 100Hz, Duty cycle; 50%, pulse width; 50 µs, pulse amplitude; 140 mA) for training regime of 2 seconds.

In healthy human, slowly increasing the pulse frequency from 20Hz result in individual muscle fibre to twitches (40 -100 ms) up to one convergence point where all individual fibre forming one smooth contraction (i.e. tetanus). But for paralysed muscle, the tetanus contraction only started at frequency around 40Hz and above (Baker et al., 2000; Fornusek et al., 2004). Biphasic pulse reduce the skin irritation as found in monophasic pulse, where it help balancing the summation of charge in the tissue due to the symmetrical pulse (Balmaseda, Fatehi, Koozekanani, & Sheppard, 1987). By the same token, biphasic pulse wave stimulation provide more comfort compared to medium frequency stimulation (Bowman & Baker, 1985).

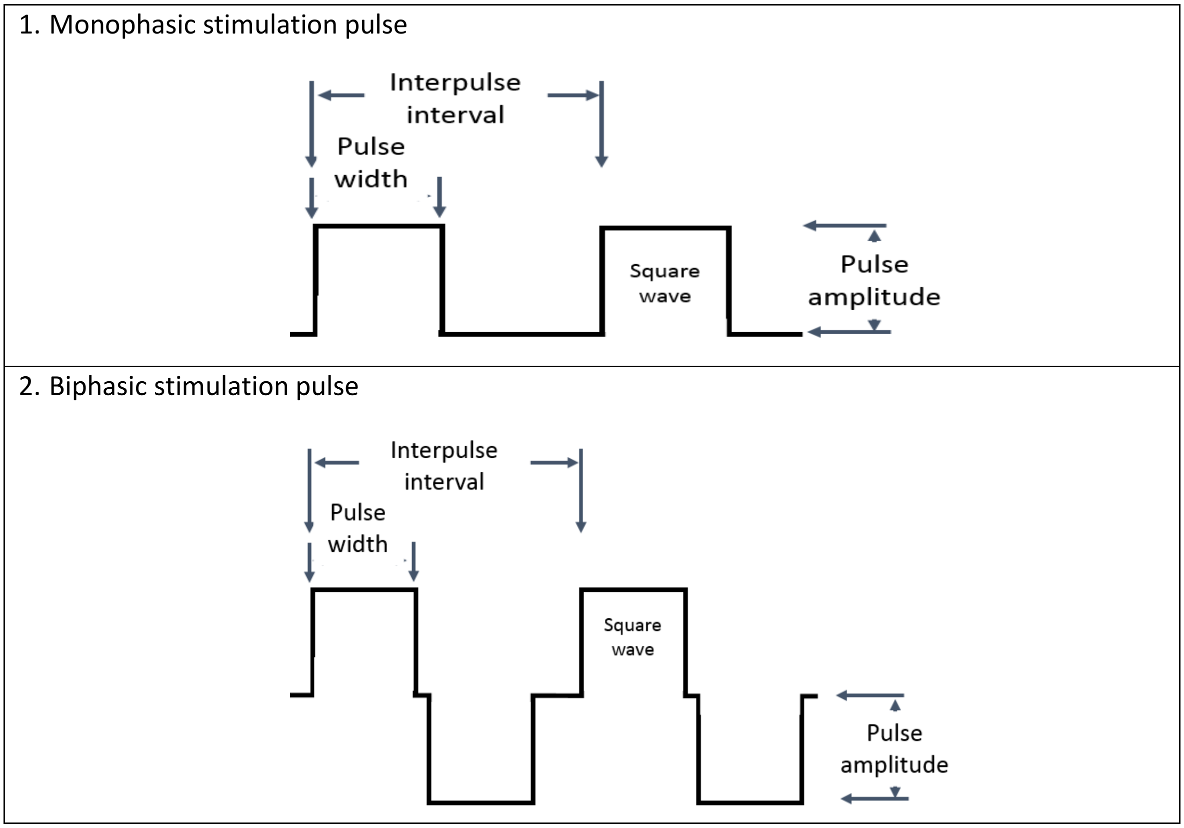


Figure 2-2 The example of monophasic and biphasic stimulation together with the pulse amplitude and interpulse interval.

2.2. Component of Functional Electrical System

Up to date, there are many FES system that had been develop and proposed which mainly for rehabilitation exercise (Bremner, Sloan, Day, Scull, & Ackland, 1992; J. J. Chen, Nan-Ying, Ding-Gau, Bao-Ting, & Gwo-Ching, 1997; Lynch & Popovic, 2008). A typical design of FES consist of a command interpreter, pattern generator, driving stage and feedback controller. Each block serve a different functional operation. The command interpreter used to receive training parameter inputs. Then, the desired waveform from interpreter input was generated by the pattern generator. The driving stage is used to regulate a constant-voltage or a constant-current source. Ultimately, feedback controller is used to regulate the feedback by automatically adjusting the FES parameter. Previous FES blocks being develop as well as the performance used in each design is summarized in Table 2-1.

2.2.1. Pattern generator

A conventional method to generate pulse pattern was using two 555 IC configuration act as analogue oscillator with adjustable pulse frequency, width and duty cycle. But, the trend to generate a series of electrical pulses using digital signal processor (DSP) device with flexible amplitude, pulse width and pulse frequency become common norm. The pulse pattern can be generated using various microcontroller (e.g., Am9513, TMS320C32 or PIC16F84, Texas Instrument) (Fornusek et al., 2004; Han-Chang et al., 2002; Kaczmarek, Kramer, Webster, & Radwin, 1991). Wide range of unique stimulation pattern can be defined using element-envelope method but significantly use less memory in the microcontroller (Han-Chang et al., 2002). In different approach, a triode break over characteristic and zero-voltage switching resonant technique was used to generate bipolarity pulse (Azman, Naeem, & Mustafah, 2012; Cheng et al., 2004; Haibin et al., 2012) .

2.2.2. Driving stage

The driving stage is the most important section in FES as it responsible to regulate a constant-voltage or a constant-current source. The output from the monostble and astable signal was feed in into driving stage. In typical FES design, the voltage compliances are in the range of 100 V to 300 V (Han-Chang et al., 2002). Initial design commonly used transformer. The error and signal pulse amplitude will be regulate before feed into the transformer. The transformer then will step up the output voltage from 9V to 200V. But, introduction of transformer make the design bulky and the most expensive component in the design (Cheng et al., 2004; Velloso & Souza, 2007a).

Next, a novel design based on a zero-voltage switching resonant method with an advantage of not requiring transformer and avoid the necessary to handle the small mark-space ratio of the pulse was introduced. Unfortunately, these design was unsuitable for closed loop design as only the pulse amplitude can be easily manipulate by changing the resistant value. For the pulse width and pulse frequency, the parameter changes dependent on diode off state and frequency of gate signal (Cheng et al., 2004). Using high voltage (i.e., ± 400) NPN (ZTX458) and PNP (ZTX558) transistor was used to inject varied amplitude pulsed DC current (>100mA) into muscle. The parameter being control by manipulating a linear voltage controlled resistor for the pulse amplitude (Debabrata, Madhurendra, & Suman, 2012).

Another design of driving stage was by a voltage control current source (Masdar, Ibrahim, & Mahadi Abdul Jamil, 2012; Thorsen & Ferrarin, 2009). Basically, the proposed circuitry was having the two transconducatance amplifier embodied together with field effect transistor. By doing this, the current amplitude can be manipulate by changing a resistor. The design had and balanced biphasic current output with a very low leakage current to ground as well as using low quiescent power consumption (Thorsen & Ferrarin, 2009). Although the design have degree of freedom in controlling the DC pulse parameter such amplitude, low development cost and not required the used of transformer but this design was never tested on real patient.

An enhanced Holland architecture were used as they advantage from their linear voltage to current conversion (i.e., high accuracy). Furthermore, ability to work on 800V Vcc allow this topology to deliver current pulse on a dense array (1mm diameter electrode) which to be place on the fingertip (Poletto & Van Doren, 1999). But, apart from having the needs to use high precision resistor, the requirement to use large resistor introduce self-oscillation in the feedback path (Han-Chang et al., 2002). To add to that, the design was disadvantaged by "common mode latch up" where the low voltage supplies achieve steady state right after power up compared to the high-voltage supplies. Besides that, Poletto and Van Doren’s design was purposely designed to deliver only monophasic stimulation only (Poletto & Van Doren, 1999).

In another design, the FES-Cycling rehabilitation system first amplified the input current from microcontroller into desired analogue current amplitude using an inverting Op-amp circuit (i.e., TL072BCJG, saturation voltage = ± 15V), then a Wilson current source topologies guide the amplified current to the output channel. To add to that, the Wilson current source topology responsible to make up the high voltage (i.e., V_{high}) that necessary to inject the current by passing the skin impedance.

2.2.3. Feedback controller

A FES can be design to have open loop or closed loop system. Open loop system means the operator will control the output of FES parameter based on their feeling and experience. Due to its relatively simple implementation, the system does not take any account from the muscle physiologically input (e.g., fatigue or load changes) (Azman et al., 2012). In a closed loop system, the FES will regulate the parameters based on the returned feedback signals from muscle physiology as shown in Figure 2-3. This configuration have the advantage of operator experience independent. However, to come out with stable control algorithm remain a challenge (Le, Markovsky, Freeman, & Rogers, 2010).

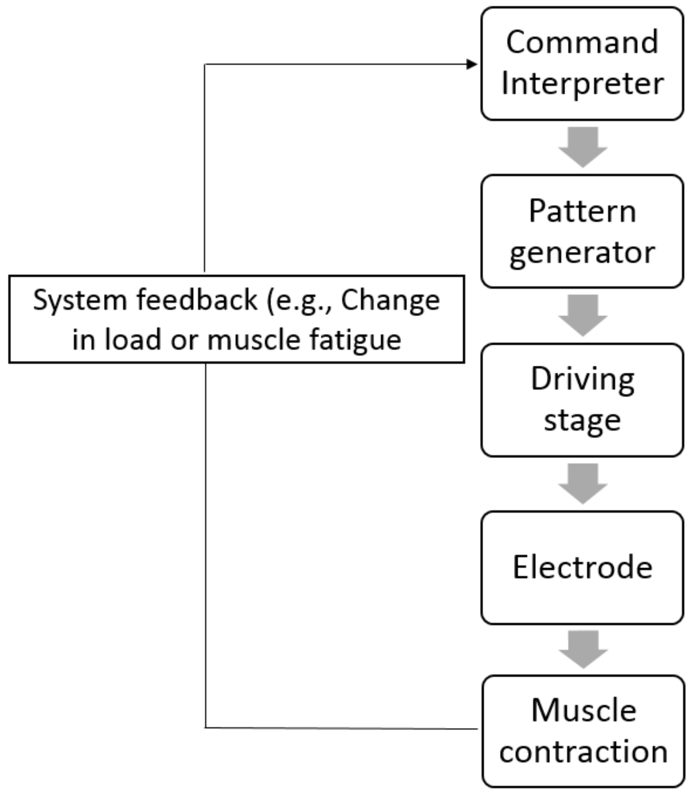


Figure 2-3 The FES with a feedback system.

Table 2-1 Table show the summarization of various FES blocks being develop as well as the performance used in each design.

FES block	Author	Notable Feature	Drawback
Pattern generator	(Han-Chang et al., 2002)	A flexible yet unique stimulation pattern of amplitude, pulse width, and pulse frequency was generated using a digital signal processor using element envelope method	~
	(Haibin et al., 2012)	Bipolarity pulse were generated using triode break.	~
Driving stage	(Millar, Barnett, & Trout, 1994)	An enhanced **Holland architecture** were applied for their linear voltage to current conversion and bi phasic wave.	But, it suffer from the needs to use high precision resistor and the requirement to use large resistor introduce self-oscillation in the feedback path. Furthermore, the usage high-voltage transistor make this architecture unsuitable for FES application that have multiple parameter as it produce unpredictable and unstable output.
	(Cheng et al., 2004; Velloso & Souza, 2007b) (Velloso & Souza,	Adjustable pulse frequency, pulse width and duty cycle with the analogue oscillator (i.e., 555 IC).	The design is bulky and expensive due to the introduction of transformer.
	(Cheng et al., 2004)	A zero-voltage switching resonant method which do not required transformer.	The pulse width was limited to on-off of diode state and frequency of gate signal. This limited their application for a closed loop design.
	(Poletto & Van Doren, 1999)	For a dense array electrode application, an 800V was used to deliver 1mA to maximum 25mA DC using the Howland structure. Having the capability outputting a wide dynamic range of electocutaneous stimulator,	Complex ways of stacking high voltage source being stacked (i.e., two 200V and two 230V) to provide ±430V to one of the Op amp terminal. Furthermore, "common mode latch up" was a major drawback.
	(Khosravani, Lahimgarzadeh, & Maleki, 2011)	Wilson current source topologies guide the amplified current to the output channel. To add to that, the Wilson current source topology responsible to make up the high voltage (i.e., V_{high}) that necessary to inject the current by passing the skin impedance. Unfortunately, the electrical schematic diagram.	Since the design were not mean to be portable, researcher was using main power supply which then being step down using step down transformer. The transformer also act as isolation from the mains supply.

	(Han-Chang et al., 2002)	A stable constant –current source with the integration of modified Wilson current mirror into the Holland architecture.	~
	(Debabrata et al., 2012)	Two transistor npn (ZTX458) and pnp (ZTX558) was used to inject varied amplitude pulsed DC current (>100mA) into muscle. The parameter being control by manipulating a linear voltage controlled resistor for the pulse amplitude. The provided schematic diagram was not clear for a good review.	~
	(Thorsen & Ferrarin, 2009)	In this design, a voltage control current source was introduced. Basically, the proposed circuitry was having the two transconducatance amplifier embodied together with field effect transistor. By doing this, the current amplitude can be manipulate by changing a resistor. The author claimed that their design had and balanced biphasic current output with a very low leakage current to ground as well as using low quiescent power consumption.	~
Feedback controller	(Veltink, Chizeck, Crago, & El-Bialy, 1992)	PID controller	~
	(Abbas & Triolo, 1997)	Artificial neural network controller	~
	(J. J. Chen et al., 1997)	Fuzzy controllers	~

2.3. Safety criteria

The concern about patient safety is one of the major consideration as the device operated in high voltage and current that can potentially electrocuted the subject. Thus, precaution to ensure the subject safety and circuitry protection is necessary according to BS EN 60601-1: 1990 ‘Medical Electrical Equipment’ and BS EN 60601-2-10:2001 Part 2.10 ‘Particular requirements for the safety of nerve and muscle stimulators’ standard. This standard can be effectively refered for benchmarking the quality and safety of the proposed design .

Since FES required high voltage at the end of the driving stage, it is necessary to isolate it from main circuit component. For a FES system that used transformer, it can act as the device to amplify the voltage as well as isolation it from the main circuit (Cheng et al., 2004). However, a design that use DC-DC converter to get high voltage stimulation usually use optical-isolated amplifier (Haibin et al., 2012). Both of the designs prevent electric shock to the patient whenever there is current or voltage leakage, system failure or anything that can damage the electrical architecture. Furthermore, to add more safety, battery powered system was used. The BS 5724 Clauses stated 70% increase in safety for a battery powered stimulator. It is also importance to include emergency stop switch to shut down all FES activity (British-Standard, 2005a).

2.4. FES operating condition

As mentioned in section 2.2.3, the FES can be regulated either manually by the operator (i.e., open loop) or automatically by various closed loop feedback system.

2.5. The Neuromuscular stimulator

Most current FES can deliver a wide range and constant current stimulation as discussed in section 2.2.1 and 2.2.2. In addition, programmable microcontroller allows multiple preset stimulation parameter which can be prescribed for specific patients or exercise activity (Fornusek et al., 2004; Mulder, Hermens, Janssen, & Zilvold, 1989). Moreover, the number of stimulation channel can be increased up 6 channel in certain design depending on the limb range of motion (Davis et al., 1990; Simcox et al., 2004).

To minimize the overall design cost, the selected electrical component and overall design should consider the cost to be as low as possible. The use of transformer (i.e. large magnetic component) in a design does not only make the design bulky , but it can be the most expensive component in the circuit (Cheng et al., 2004). The design should be small, compact and portable for easy handling and mobilizing. Other research that develop their own device, but lack of explanation and with no circuit diagram are listed in Table 2-5.

Table 2-2 show the summarize of FES safety criteria

Design criteria	1. (Velloso & Souza, 2007a)	2. (O'Keeffe & Lyons, 2002)	3. (Han-Chang et al., 2002)	4. (Azman et al., 2012)	5. (Haibin et al., 2012)	6. (Khosravani et al., 2011)	7. (Masdar et al., 2012)	8. [T](Cheng et al., 2004)	9. [ZV](Cheng et al., 2004)	10. (Debabrata et al., 2012)
1. Driving stage and main circuit isolation										
a) Optical-isolated amplifier		√	√							
b) Transformer	√					√		√		
2. Power source										
a) Ac Powered	√					√		√		
b) Battery powered		√	√	√	√		√		√	√
3. The proposed design include emergency power switch	♀	♀	√	♀	♀	♀	♀	♀	♀	♀

Note. Criterion met (√**),** Criterion not met (♀)

[T] Transformer based FES, [ZV]Zero-voltage switching resonant technique

Table 2-3 FES operating condition

Design criteria	1.(Velloso & Souza, 2007a)	2.(O'Keeffe & Lyons, 2002)	3.(Han-Chang et al., 2002)	4.(Azman et al., 2012)	5.(Haibin et al., 2012)	6.(Khosravani et al., 2011)	7.(Masdar et al., 2012)	8.[T](Cheng et al., 2004)	9.[zv](Cheng et al., 2004)	10.(Debabrata et al., 2012)
4. Stimulation parameters was regulated by										
c) Closed loop feedback		√	√	√ [3]		√				√
d) Open loop	√				√		√	√	√	√

Note. Criterion met (√**),** Criterion not met (♀)

[1]PID Controller, [2]Artificial neural network, [3]Fuzzy controller, [T] Transformer based FES

Table 2-4 The Neuromuscular stimulator

Design criteria	1.(Velloso & Souza, 2007a)	2.(O'Keeffe & Lyons, 2002)	3.(Han-Chang et al., 2002)	4.(Azman et al., 2012)	5.(Haibin et al., 2012)	6.(Khosravani et al., 2011)	7.(Masdar et al., 2012)	8.[T](Cheng et al., 2004)	9.[zv](Cheng et al., 2004)	10.(Debabrata et al., 2012)
5. No of stimulation channel	4	2	4		2	6	1			4
6. Possessed adjustable a) pulse charge										
I.pulse amplitude (mA)	0~100	120	0~110	15~100	100	0~150	10-120	100	100	0~100
II.pulse width (µs)	50~500		50				10~500	√	20	10~500
b) frequencies (Hz)	20~200	√	3~100		10~60	59		√	√	5~100
c) Wave shape										
I.Biphasic	√	√	√ [1]	√	√	√	√	√	√	√
II.Monophasic.		√								
d) Duty cycle	√	√				√		√	√	√
7. Delivered precise constant current under varying load	≠	≠	√ [2]	≠	≠	√ [2]	≠	√[3]	≠	≠
8. The finish design should be small and portable	♀	√	√	√	√	♀	√	♀	√	√

Note. Criterion met (√**)**, Criterion not met (♀), Criterion has not been mention in any literature (≠)

[1] Waveform pattern envelope based on element-envelope method, [2] Wilson current mirror, [T]Transformer based FES, [3]Feedback loop

Table 2-5 show research that develop their own device but with no circuit diagram explanation.

Author and year	Research title
Buckett, Peckham, Thrope, Braswell, & Keith, 1988	A flexible, portable system for neuromuscular stimulation in the paralyzed upper extremity
(Buckett, Peckham, Thrope, Braswell, & Keith, 1988; Chiou, Chen, Lai, & Kuo, 2004	A non-invasive functional electrical stimulation system with patient-driven loop for hand function restoration
Del Pozo & Delgado, 1978	Hybrid stimulator for chronic experiments
Krenn et al., 2011;	Safe neuromuscular electrical stimulator designed for the elderly
Loeb et al., 2004	RF-powered BIONs for stimulation and sensing
Lyons, Sinkjaer, Burridge, & Wilcox, 2002;	A review of portable FES-based neural orthoses for the correction of drop foot
Sabut & Manjunatha, 2008;	Neuroprosthesis-Functional Electrical Stimulation: Opportunities in Clinical Application for Correction of Drop-Foot
Simpson & Ghovanloo, 2007	An Experimental Study of Voltage, Current, and Charge Controlled Stimulation Front-End Circuitry.
Xikai, Jian, Liguo, Qi, & Jiping, 2012	Design of a wearable rehabilitation robot integrated with functional electrical stimulation

Chapter 3. METHODOLOGY

3.1. System design

The advantage of FES in the rehabilitation field is well described in many literature. But, commercial available FES device is hard to tailor to suit with one's research objective. Thus, a new custom-made FES with specific design criteria (DC) was develop. The main design criteria of the FES device were 1) safe and 2) research oriented design. Design criteria consideration of the FES are explained in detail below.

3.1.1. Safety

This device operated in high voltage and current that can potentially electrocuted the subject. Thus, precaution to ensure the subject safety and circuitry protection is necessary and the following requirements were considered in the design.

DC1. The FES device was battery powered.

DC2. Emergency switch button was included and placed at a position easily reached by the patient or operator. Emergency stop button is compulsory in the design for an emergency stop. This button makes all electrical activity halt.

3.1.2. FES operating condition.

The device was developed specifically to change the stimulation parameter automatically depending on the muscle fatigue level to prolong the FES exercise.

DC3. The FES device is able to regulate the stimulation parameters based on closed loop feedback.

3.1.3. The Neuromuscular stimulator

Consideration such ability to be used for research purposes were greatly consider as explained below.

DC4. Has at least one stimulation channels.

DC5. Has adjustable pulse charge (i.e., pulse amplitude and pulse width), frequencies, wave shape (i.e., biphasic and monophasic), and duty cycle.

DC6. Able to deliver precise constant current under varying load.

DC7. The final design should be small and portable.

3.2. Proposed stimulator

The important component of the proposed design are pattern generator, high voltage switch, driving stage (i.e., voltage to current converter with Wilson current mirror integration). The interaction between the FES2013 components is shown in Figure 3-1. Basically, current from the high voltage supply will flow through the, driving stage, high voltage switch, and electrode and terminated at the ground. The pattern generator (i.e., Arduino) will control the ON-OFF of the high voltage switch. The duration of the on-off will determined the pulse width and frequency. A square wave will be produce from the ON-OFF of Arduino activity.

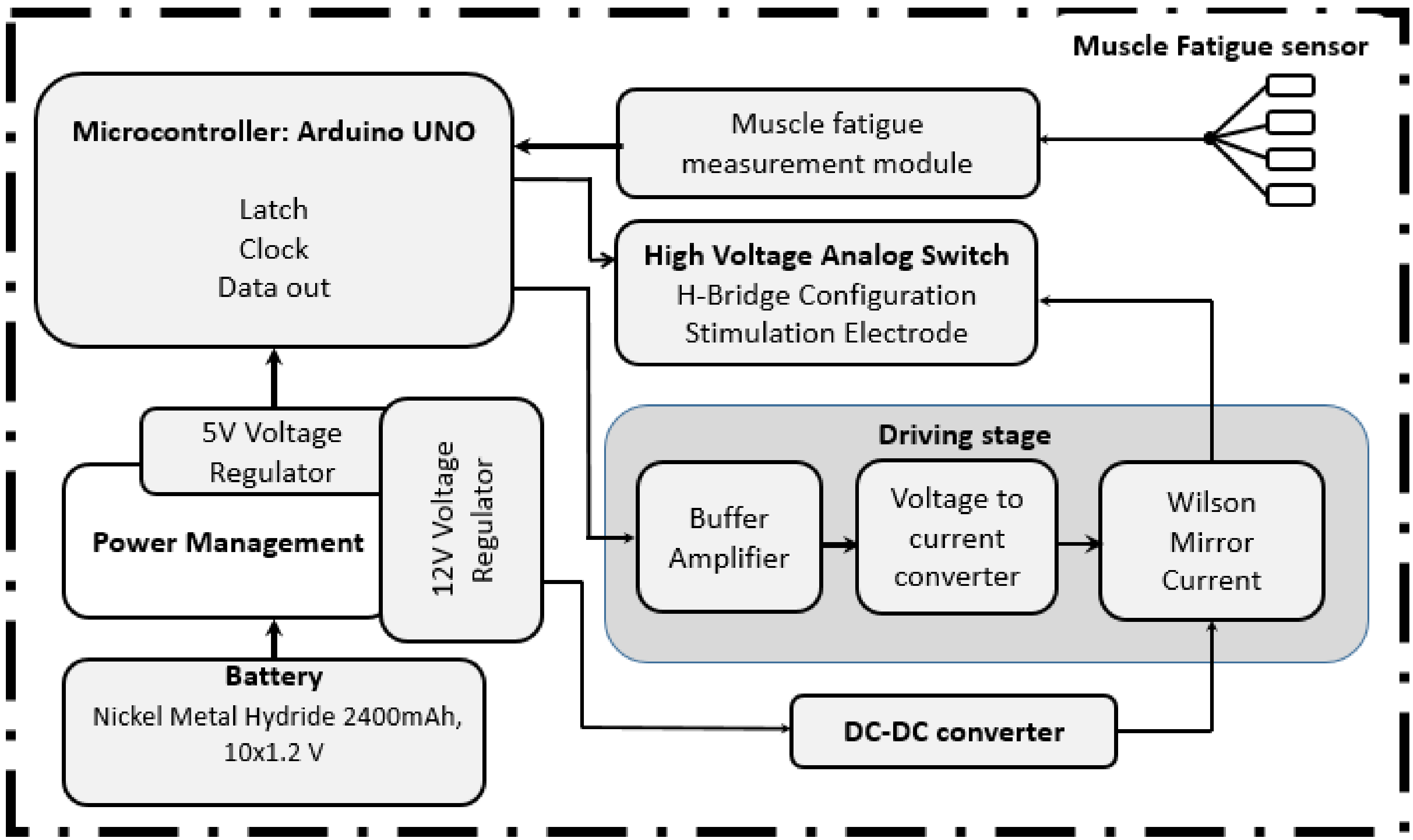


Figure 3-1 The interaction between the FES2013 components

3.2.1. Driving stage

The FES2013 was powered by 10 batteries (**1.2V, 1800 mA, Everyday**) stacked in series to give a 12V power supply. To have a compact design, the same 12V battery power is used to power up the Arduino (5V input supply) and miniature voltage DC-DC converter (12 input supply) with each regulated by 5V (**MC78LC50HT1G**) and 12V (**LM340T-12**) voltage regulator.

The 200V high voltage power is generated from The DC-DC converter (GMP12-200 HICOM) with input supply of 12V. With power capacity of 1.5W, the DC-DC converter can supply maximum 7.5mA continuous current at 200V as shown in equation 1.

$$\boldsymbol{continous\ Current = \frac{Power}{Voltage}} \qquad \textbf{Equation 1}$$

This enable the chosen DC-DC Converter to supply enough current at maximum training parameters (i.e., pulse amplitude: 100mA; pulse width: 500µs; frequency: 100Hz: 75% duty cycle) which correspond to continuous current of 3.75mA as shown in equation 2,

$$\boldsymbol{Continous\ current = pulseamplitude * pulsewidht * dutycycle * stimulationfrequency} \qquad \textbf{Equation 2}$$

3.75mA = 100mA * 500 µs* 100Hz* 0.75

To protect the circuit due to short circuit, a fuse (0.25A, 250V) is introduced. To ensure the linearly converted voltage does not exceed 200V, Zener diode (**D1**) and resistor (**R5**) was placed right after the GMP12-200 output.

3.2.1.1. H bridge switch formation

Selection of HV2201PJ-G (low Charge Injection, 8-Channel, Enhanced, High Voltage Analog Switch, Supertex, Sunnydale, CA) allow the formation of H bridge switch as shown in Figure 3-2 easily. HV2201PJ use a low voltage 8-bit shift register (0 or 5V) to control on-off high voltage (200V) switching. The 8-bit shift register of HV2201PJ needs only three control pins (i.e., CLK, LE, and CLR).

One channel FES can be obtain using a single H bridge switch configuration by utilizing 4 (i.e., SW0, SW1, SW2, SW3) out 8 switch from HV2201PJ. To produce monophasic pulse polarity, the current i_{load}, from Wilson current mirror will pass through first high voltage switch, to the positive site of electrode, then to the second high voltage switch and finally terminated to ground as indicate by the blue arrow flow in Figure 3-2. In other word, the monophasic (positive pulse) waveform generated by closing SW0 and SW1 simultaneously for certain time. To generate biphasic waveform, the SW0 and SW1 (positive pulse) was closed simultaneously, then open close SW0 and SW1 followed by closing SW2 and SW3 (negative pulse) simultaneously.

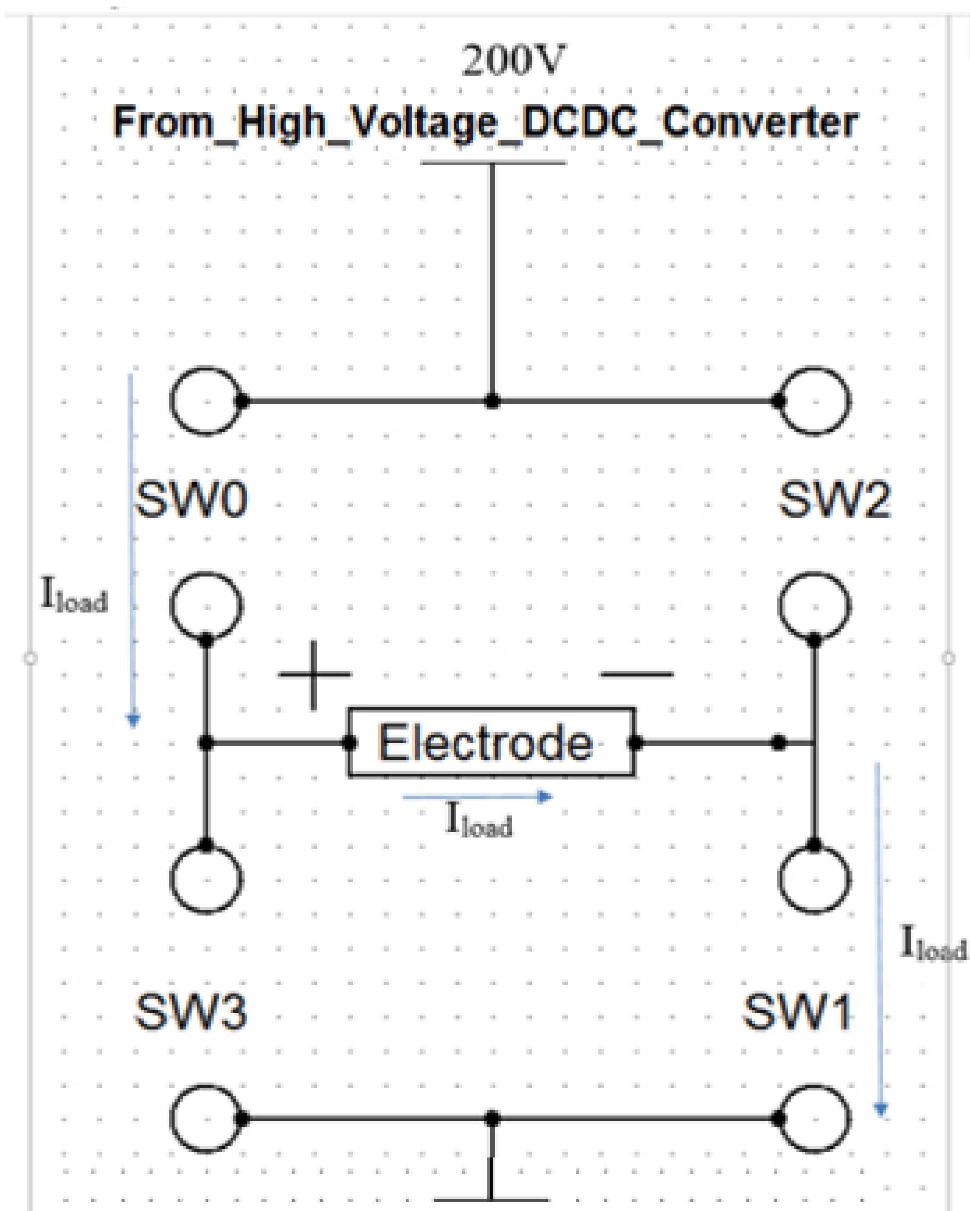


Figure 3-2 H bridge switch formation.

3.2.1.2. Voltage to current converter (Transconducatance amplifier)

The arduino through the R2R resistor ladder will regulate the pulse amplitude through the buffer amplfier and voltage to current converter as shown in Figure 3-3 . The buffer amplifier ensured that the output voltage V_1 followed the input signal over the U2A. The voltage to current converter (i.e., U1A & Q3) act to supplies current $\mathbf{i_1}$ by controlling voltage ($\boldsymbol{V_{ref}}$). The configuration used was " voltage to current with grounded load" which will give proportional voltage signal to output current (Salivahanan, 2008). Since U1A have high gain, V_{ref} will approximately equal to V_1. Therefore, the current flow from bipolar junction transistor (Q3) emiter,

$$\boldsymbol{i_1 = \frac{v_1}{R_3}} \qquad \textbf{Equation 3}$$

And

$$\boldsymbol{I_2 = \frac{\beta}{\beta+1} I_1} \qquad \textbf{Equation 4}$$

Therefore, the reference voltage is converted into a current source.

The Wilson current mirror (Q1, Q2 & Q4) configuration will reflect an identical current value to the load and allows the load to be grounded as shown in Figure 3-3. Selecting Q1 and Q2 to have similar current gain β, then the output current of the current mirror I_{load} was

$$I_{load} = \frac{1}{1 + 2/(\beta^2 + \beta)} I_2 \qquad \textbf{Equation 3}$$

Since Q3 have β ≈ 100, and R3 = 18 Ω was chosen so that the maximum pulse amplitude (140 mA**).** Therefore, the resolution for the voltage to current converter is

$$\frac{I_{load}}{v_1} = \frac{0.99}{R_3} = g_m \approx 55\, mA/V \qquad \textbf{Equation 4}$$

Theoretically, the resolution of the voltage to current converter is independent of load resistance, power supply voltage and temperature (Kaczmarek et al., 1991). On the other hand, to minimize the temperature sensitive of current mirror (Kok & Tam, 2013), two resistors (**R1 & R2**) was added to stabilize the current output.

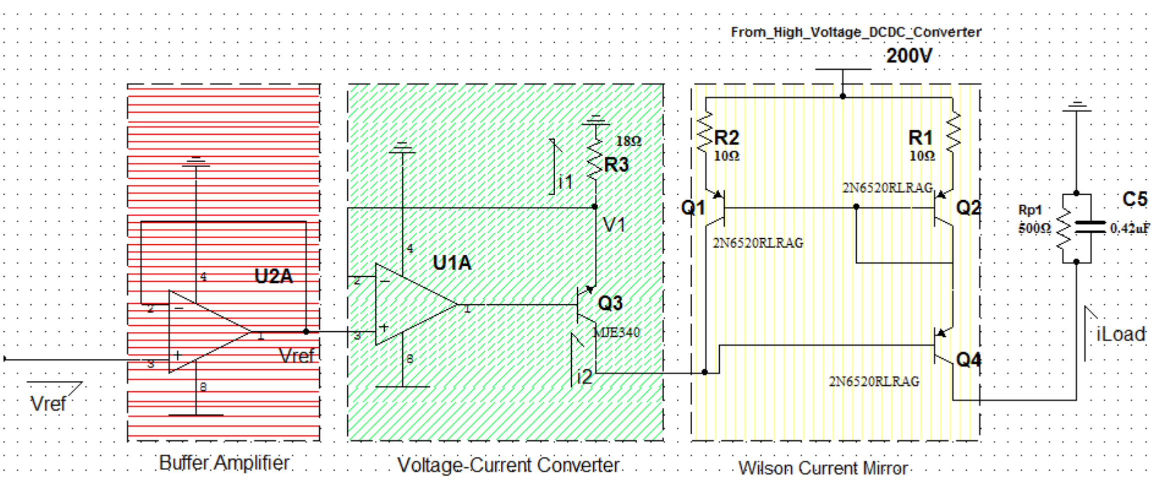


Figure 3-3 Circuit schematic of the driving stage.

3.3. *Flexible closed loop functional electrical stimulator*

The objective of this section was to demonstrate the ability of the Arduino Uno microcontroller to change its output parameter base on external input. The programmable Arduino microcontroller with embedded written C language performs all the timing function as shown in Figure 3-4. Initially, the C program will define all the necessary Input and Output Pin. Then, the potentiometer value will read by the function analogRead(potPin). After that, the three if value condition will examine with respect to the potVal variable. Then, the "for loop" will be execute with reference to the appropriate potVal variable. Once the one cycle "for loop" executed completely, the parameters output will be regulated repeatedly base on the input sensor (Voltage change from the potentiometer). The void loop (step ii to iv) will repeated continuously until user terminated the program. The Table 3-1 summarize the each rule and output to be met.

Table 3-1 summarize the each rule and output to be met.

If condition (rule)	Output
300	Set the pulse width to 50microsec and frequency to 10Hz per second.
600	Set the pulse width to 100microsec and frequency to 50Hz per second.
600 -1023	Set the pulse width to 150microsec and frequency to 100Hz per second.

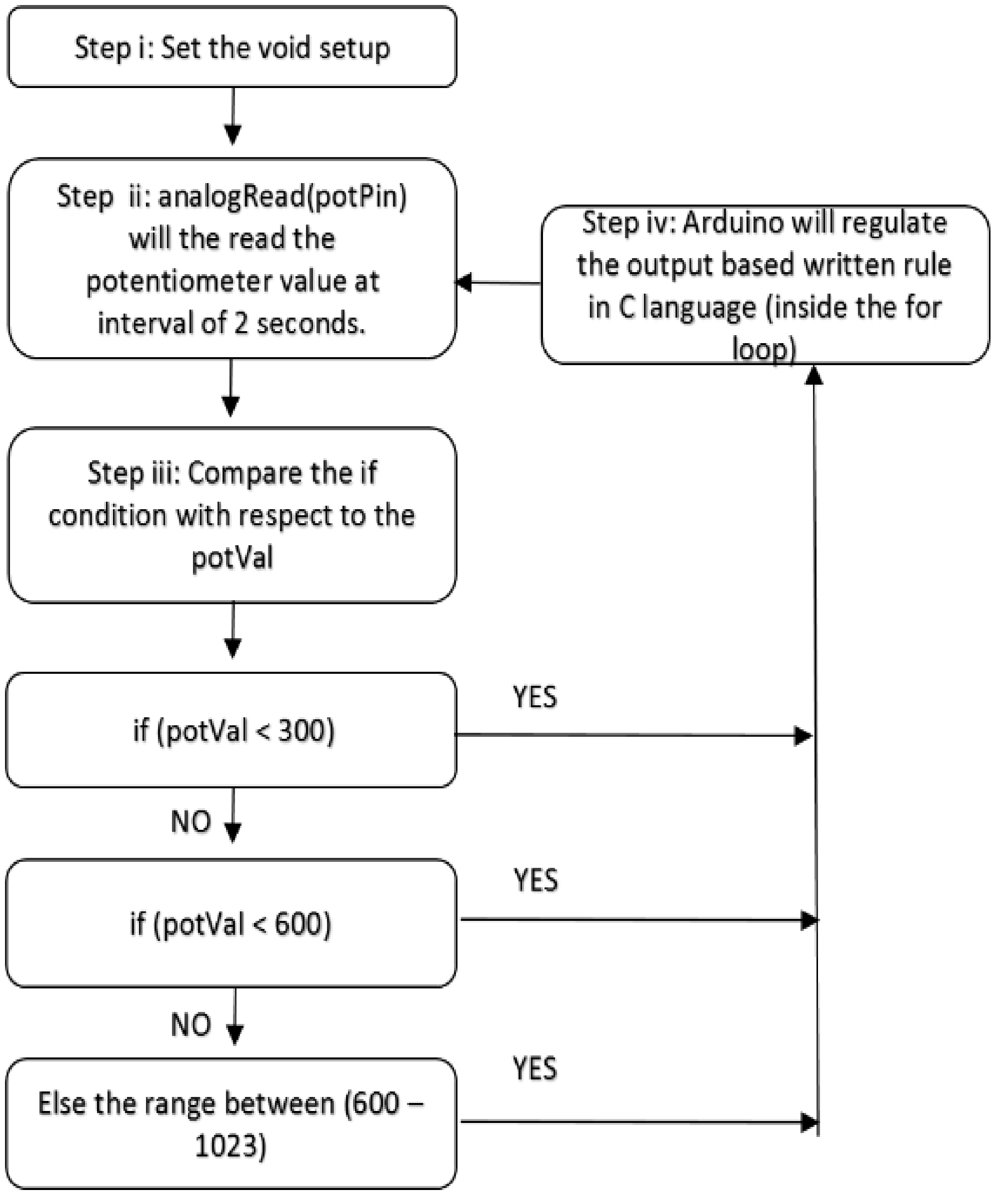


Figure 3-4. Flow diagram of the C program process by Arduino.

3.4. Performance comparison between DS2000 and FES2013

To demonstrate the stimulation performance of the FES2013, the consideration listed below was being considered.

1. The ability to deliver a precise constant current under varying load.

Performance comparison was conducted between DS2000 and FES2013 using the skin model.

3.4.1. Skin model

A first order skin model consisting a series resistor (i.e., R_S: bulk tissue resistance) with parallel RC network (R_{vary} & C_R; resistive and reactive components of the electrode/skin interface) was used to assess the ability of the DS2000 and FES2013 to deliver a precise constant current under varying load (**DC6**) as shown in Figure 3-5 (Poletto & Van Doren, 1999). The R3 (500Ω) fix value and the varying Rvary (500Ω, 700Ω, 1KΩ, 1.5KΩ) was chosen as to comply with the maximum total summation of skin resistance around 2KΩ. The MULTISIM software was used to model the voltage drop across R_{drop} for both DS2000 and FES2013 at varying current and R_{vary} as shown by the schematic in figure 1 and figure 2.

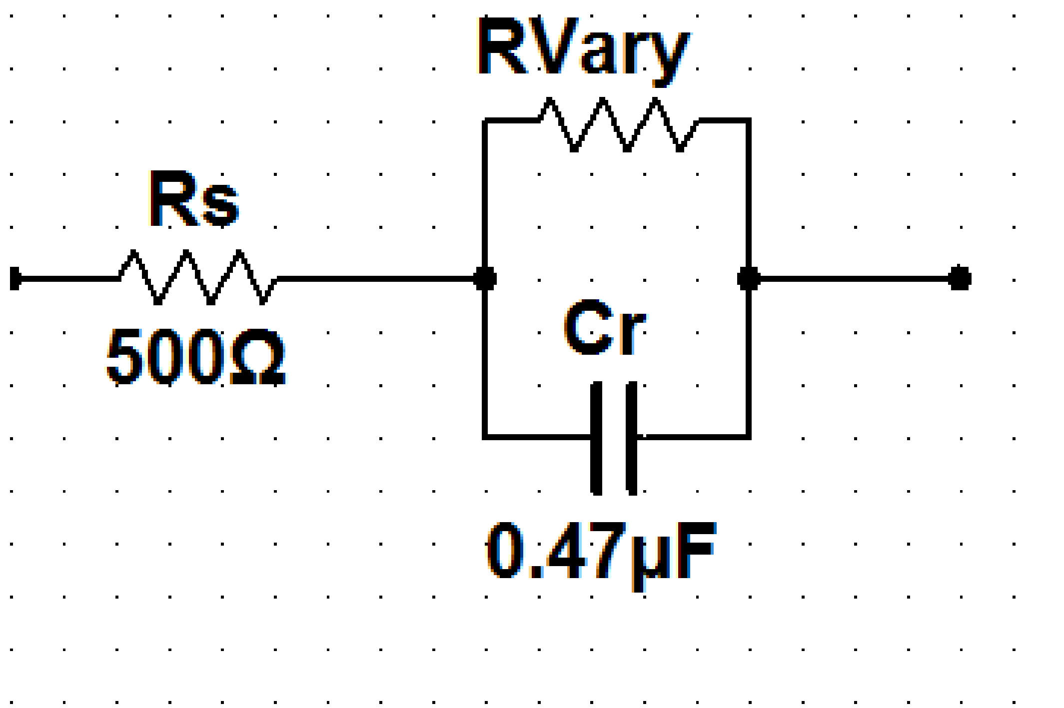


Figure 3-5 A first order skin model

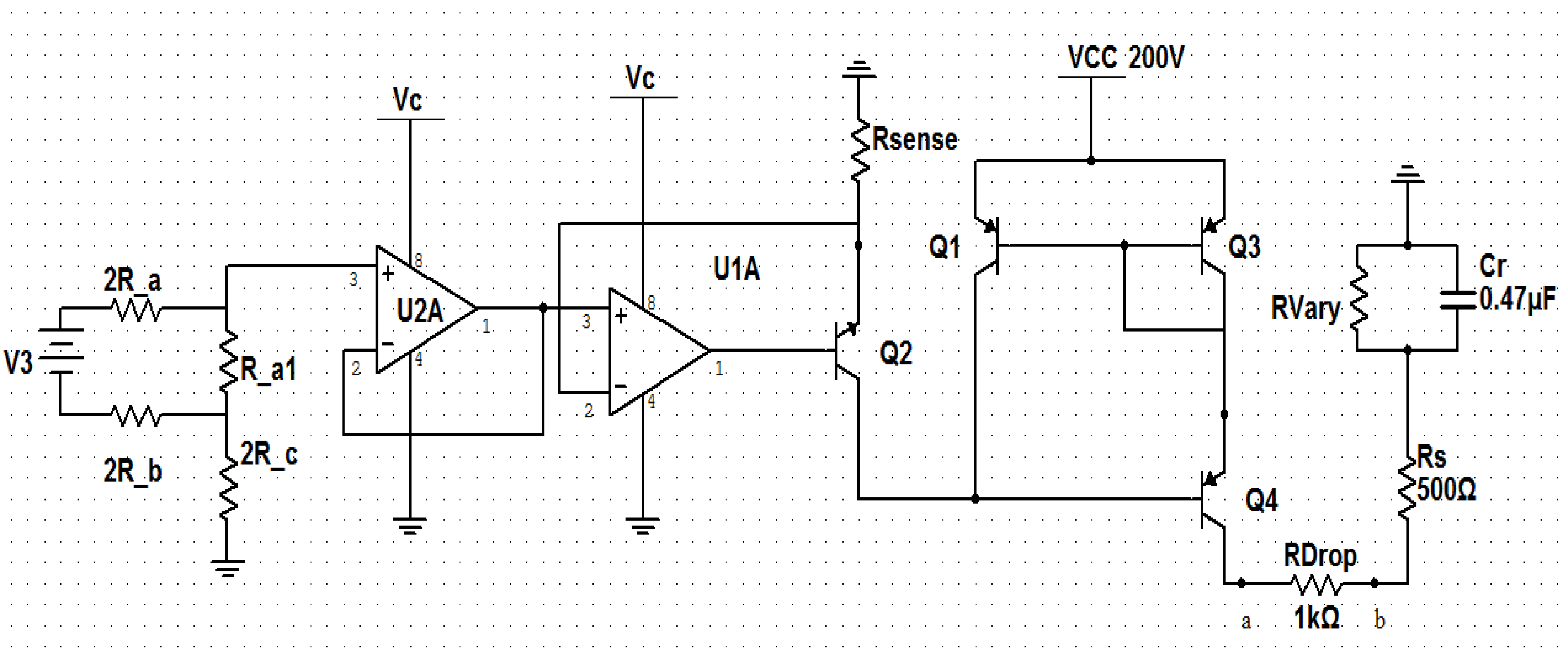


Figure 3-6 The FES2013 model in MULTISIM software for performance simulation for varying current and Rvary.

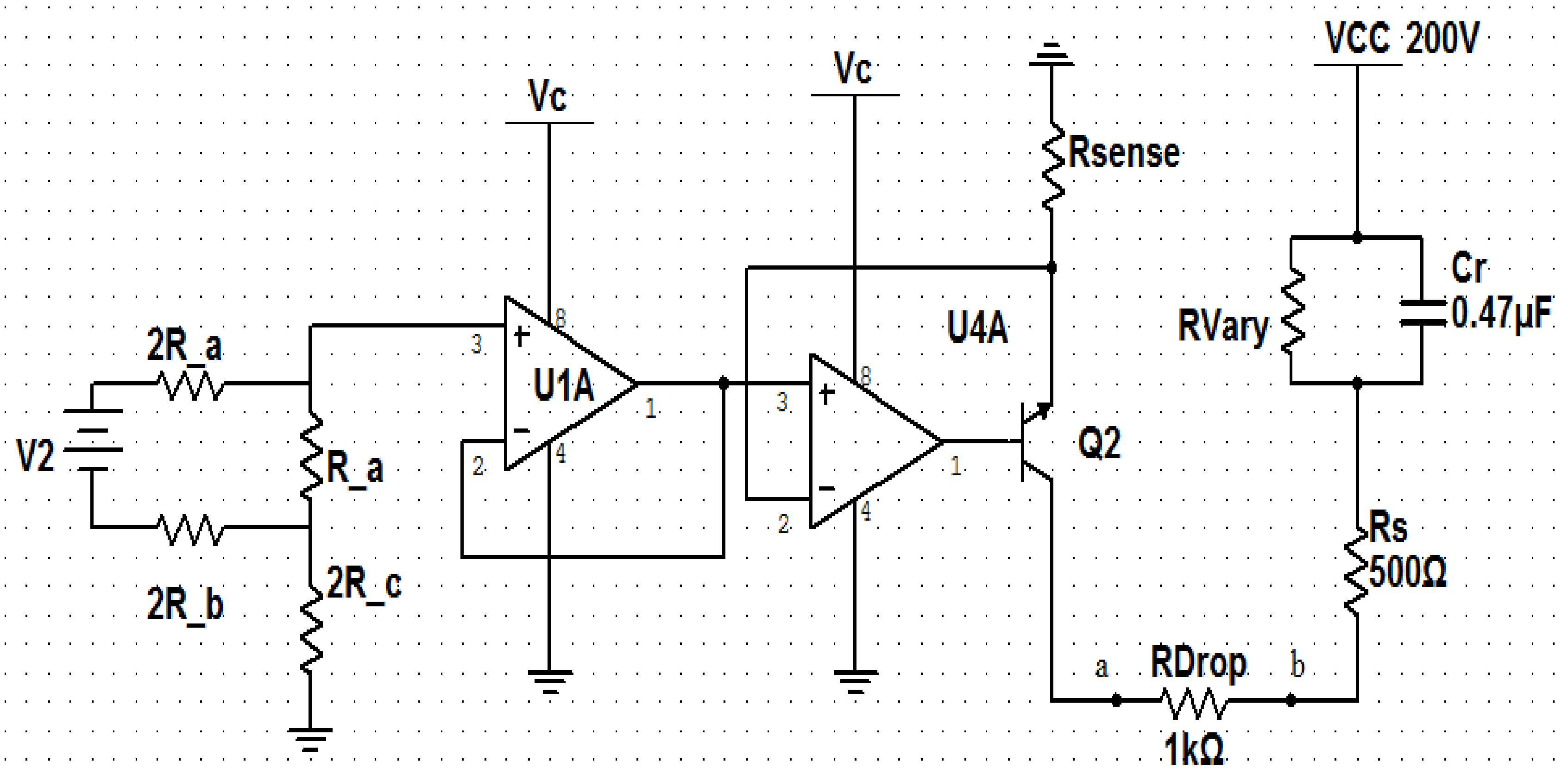


Figure 3-7 The DS2000 model in MULTISIM software for performance simulation for varying current and Rvary.

The ability to deliver a precise constant current under varying load, R_{vary} (500Ω, 700Ω, 1KΩ, 1.5KΩ) was determine based on percentage of current deviation of fix intended desired current from output current (i.e., I_{output}) that flow across R_{drop}.

I_{output} was given by;

$$I_{output} = \frac{V_{ab}}{R_{Drop}} \qquad \textbf{Equation 5}$$

Thus,

$$\textbf{percentage of current deviation} = \frac{I_{output} - \text{desired current}}{\text{desired current}} \times 100\% \qquad \textbf{Equation 6}$$

Spearmen's rho regression correlation analysis was used to analyse the correlation between intended current and percentage of current deviation for both FES2013 and DS2000 design. Mann-Whitney Exact Test 2 tailed was used to perform the statistical analysis since the calculated and recorded I_{output} data was not normally distributed and had violated the assumption of parametric tests (Field, 2005).. All statistical analysis was performed using SPSS ver. 16.0. Windows software (SPSS Inc., Chigicago, Illinois, USA).

Chapter 4. RESULT

A FES2013 FES stimulator with the ability to deliver electric pulse as summarize in Table 4-1 was shown.

Table 4-1 Theoretical output parameter can be delivered by the FES2013 [1]

Parameter	Minimum	Maximum
Amplitude (mA)	0	140
Pulse width (μs)	50	500
Frequency (Hz)	10	100
Biphasic	Yes	

4.1. Safety

The FES2013 device was battery (Battery 12V) powered (**DC1**) and had emergency switch button (Switch1) (**DC2**) included as shown in Figure 4-1.

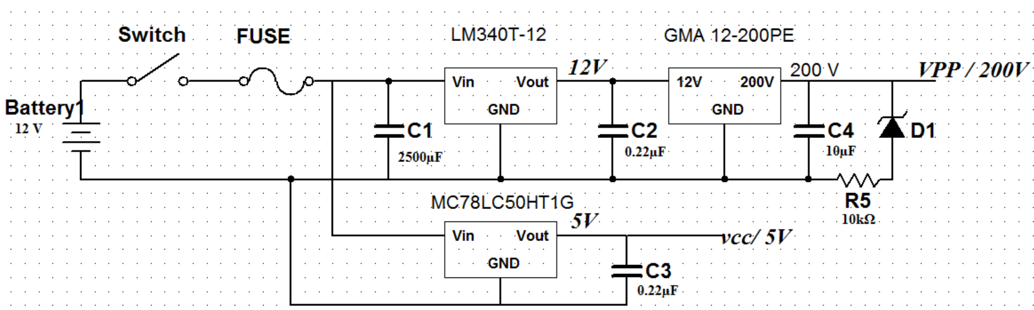


Figure 4-1 The power supply schematic with battery and switch include.

[1] Theoretical since not proven from practical testing. The figure are derived from the Arduino setup.

4.2. Flexible closed loop functional electrical stimulator

The device was developed specifically to adjust the stimulation parameter automatically depending on the muscle fatigue (**DC3** & **DC5**). The Arduino successfully outputting all the intended pulse width and frequency as dictate from the software algorithm. The square wave with their pulse width from each "if" condition was shown in Figure 4-2

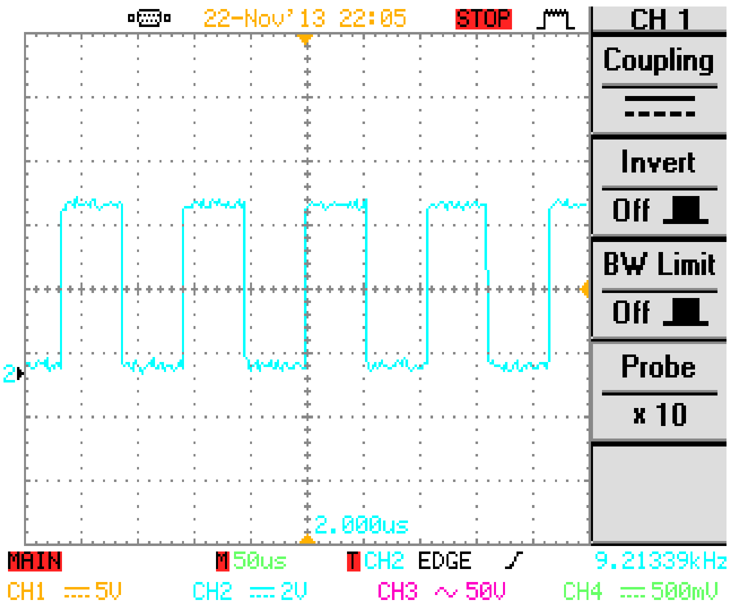
4.3. Performance comparison between DS2000 and FES2013

A simulated skin model was used to demonstrate the FES2013 ability to deliver precise constant current under varying load (**DC6**). The performance were examined using Multisim simulation software. Both design shows mean percentage of current deviation ranging 0.01% to 0.1 % for all intended current ranging 40mA to 140mA. Despite that, the FES2013 shows higher current output deviation starting from 80 mA to 120mA and drop when it was 140 mA. Nonetheless, DS2000 able to minimize the mean percentage of current output deviation from 40mA to 100mA and increase slightly from 120mA to 140mA as shown in Figure 4-3. However, the Spearmen's rho regression correlation analysis shows no correlation between the intended current and mean percentage of current output deviation for FES2013 ($p > 0.05$) and DS2000 ($p > 0.05$).

Then, the percentage of current output deviation pattern from each varying load (i.e., 500Ω, 700Ω, 1kΩ, 15kΩ) were separately analyse. Both design shows have percentage of current deviation ranging 0.01% to 0.29% for FES2013, while DS2000 around 0.005% to 0.3%. DS2000 show deviation less than 0.04% for all load except when the desired current was 120mA and 140mA for Rload (i.e., 1.5kΩ) which was around 0.3%. The FES2013 shows less current output deviation (< 0.06 %) when the desired current was 40mA to 100mA and start to increase from 120mA to 140mA regardless of R_{load} as shown in Figure 4-4. However, the Spearmen's rho regression correlation analysis shows no correlation between the intended current and percentage of current output deviation for FES2013 ($p > 0.05$) and DS2000 ($p > 0.05$) regardless of load introduce.

Overall, there is a significant difference between the two designs as shown by Mann-Whitney Exact Test regardless of the R_{load} introduce ($p < 0.05$) from the skin model performance test.

(a)



(b)

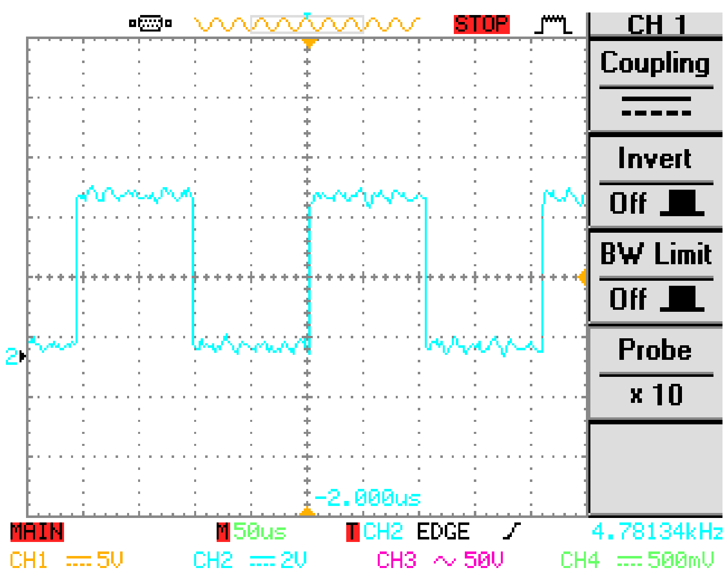


Figure 4-2 Square wave with (a) 50µ, (b) 100µ, and (c) 150µ second pulse width from the Arduino output.

(continue)

(c)

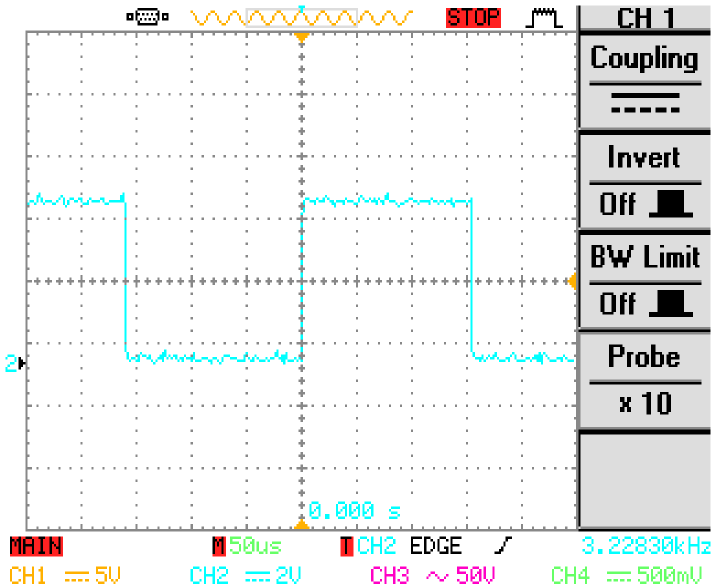


Figure 4-2 Square wave with (a) 50µ, (b) 100µ, and (c) 150µ second pulse width from the Arduino output.

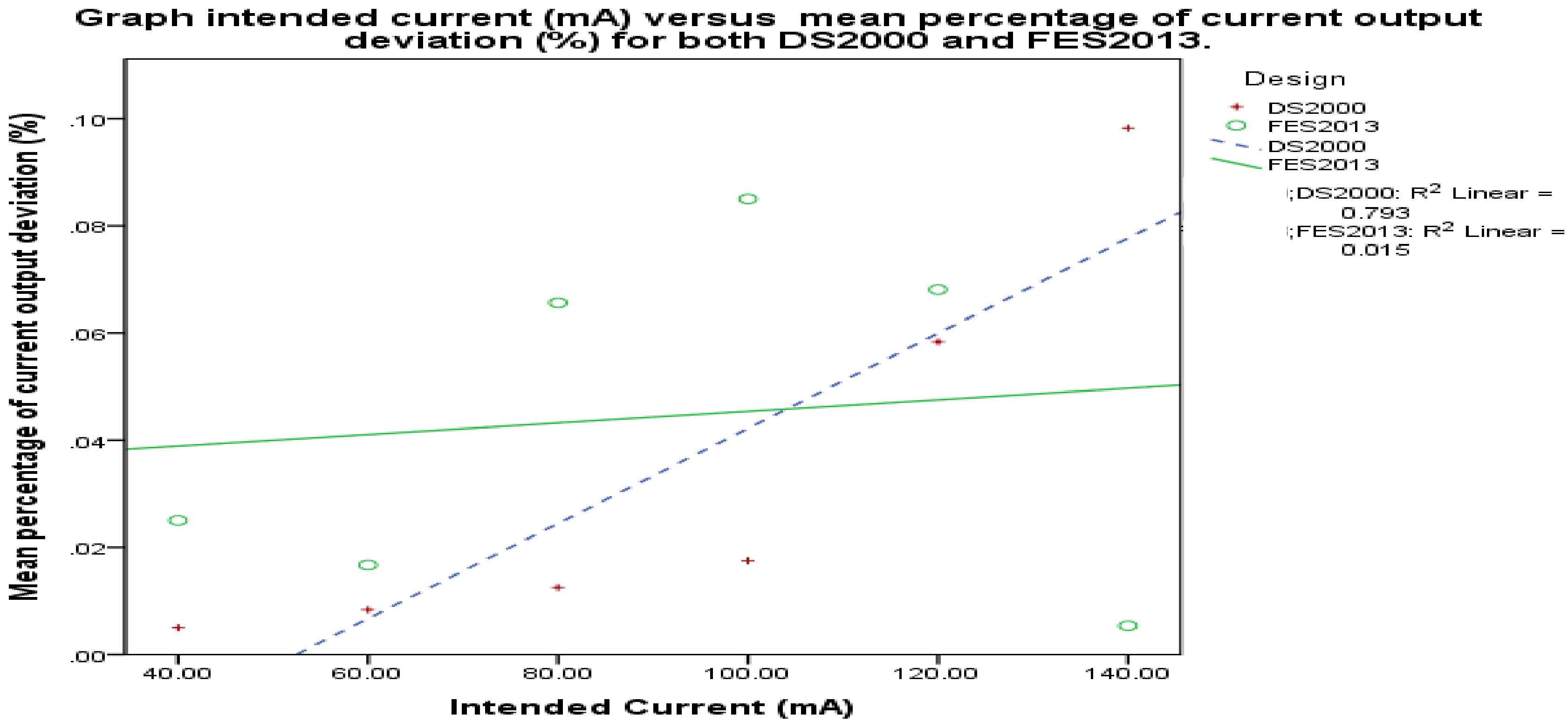


Figure 4-3. The intended current versus mean percentage of current output deviation. Current output from the varying load (i.e., 500Ω, 700Ω, 1kΩ, 15kΩ) was averaged and plotted against the intended current.

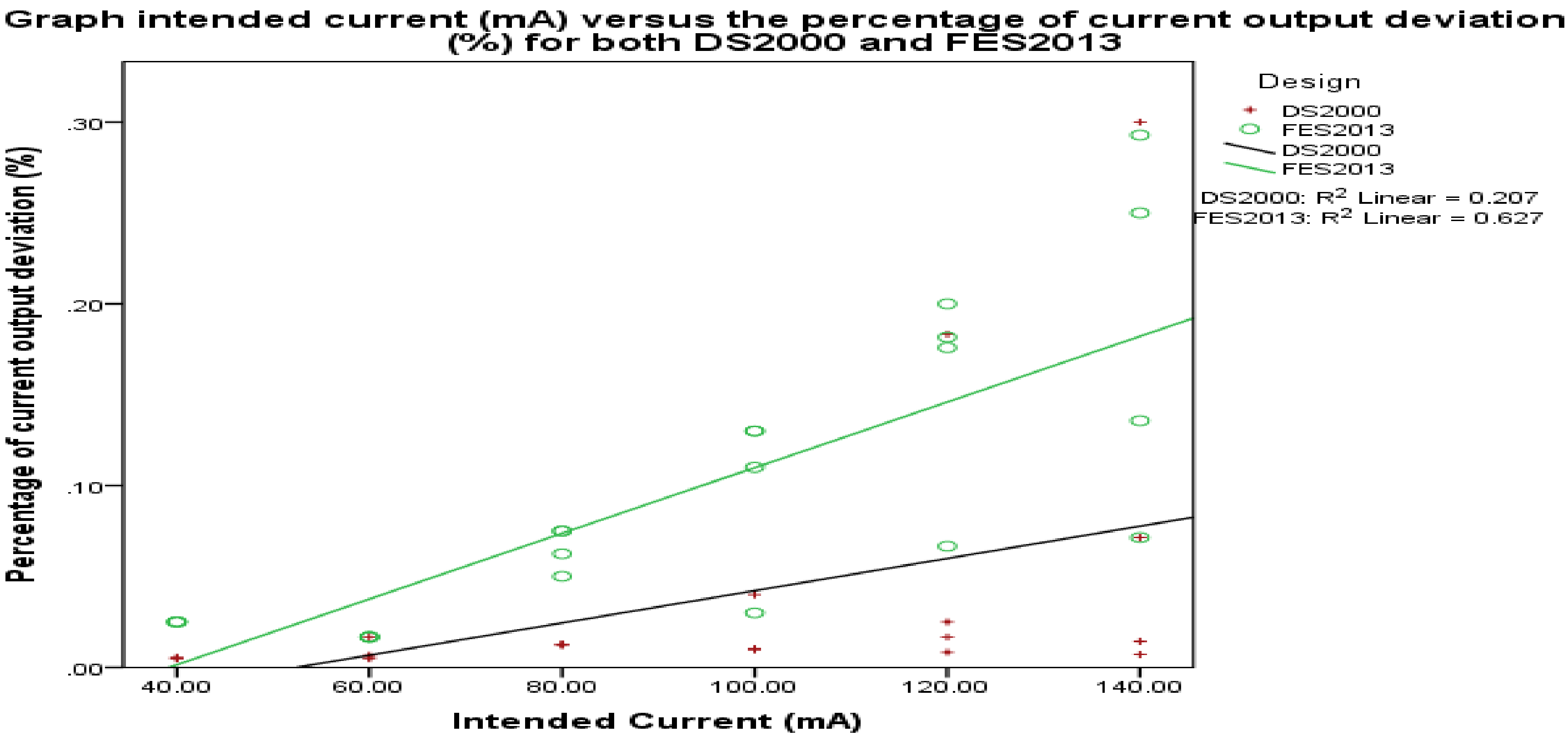


Figure 4-4 The intended current versus percentage of current output deviation. Percentage of current output deviation from each load (i.e., 500Ω, 700Ω, 1kΩ, 15kΩ) was plotted against the intended current.

Chapter 5. DISCUSSION

5.1. Design criteria of FES2013

This paper present a newly proposed non-invasive closed loop functional electrical stimulator namely FES2013 that had been partially successful developed and tested. This section will explain in detail all the best criteria from DS2000 (Fornusek et al., 2004) design that being taken for the development of FES2013. The design were successfully attain all the design criteria that describe in section 3.1. Table of summarization for the EES, DS2000 and FES2013 was tabulated in Table 5-1**.**

5.1.1. Electrical safety consideration

Several electrical safety mechanism was taken because the FES2013 was operated in high voltage and current. First, the driving stage were battery powered by 12V battery instead of using direct AC current from main power (**DC1**). Secondly, the high voltage source was from the DC-DC converter. Some researcher agree 120V ~ 220V is tolerable for the FES application (Fornusek et al., 2004; Han-Chang et al., 2002). However, the 200V output voltage from the DC-DC converter is below the restricted output voltage of 500V as recommended by BS EN 60601-2-10:2001 Part 2.10[2] (British-Standard, 2005b). To further

[2] BS EN 60601-2-10:2001 Part 2.10 .Section 8. Accuracy of operating data and protection against hazardous output. *51.104 a) Equipment intended for therapeutic applications.

increase the safety level, an emergency stop button[3] was introduced to shunt the load current when something went wrong (**DC2**) (British-Standard, 2005a).

5.1.2. FES operating condition.

Since the Arduino UNO capable of both receiving and outputting analog and digital input, there are open space that allowed more diversified closed loop control system. The close loop system can minimize the intervention by operator and fully rely on the automatic preset configuration/parameter. The system is expect to be flexible in receiving any input signal as the feedback source (i.e. EMG, Vibration &velocity) for the closed loop system (**DC4**).

The Arduino UNO chosen for this system is on par with the needs of present application of FES (i.e., processing speed & I/O capability). The FES2013 having the advantages of easy customization through encoding of the Arduino architecture which is simpler compare to conventional microcontroller (e.g., 8051 & PIC16F84 microcontroller). This is helpful especially for programming newbie to conduct FES related experiment.

Instead of using adjustable high precision resistor as seen in Polletto and Van Doren work (Poletto & Van Doren, 1999), the proposed design obtain varying current by changing

[3] BS EN 60601-1: 1990 'Medical Electrical Equipment': Clause 9.2.2.4.4 Protective measures.

the analog input voltage as explain in section 3.2.1.2. This thus avoid from having the self-oscillation in the feedback path due to high precision resistor (Han-Chang et al., 2002).

5.1.3. The Neuromuscular stimulator

The FES2013 was capable to handle more than one stimulation channel (DC5). Major improvement made from EES and DS2000 was the application of HV2201PJ-G high voltage switch. The HV2201PJ-G high voltage switch allow shorter coding line to control more than one stimulation channel. This is possible with the simplicity from the daisy chaining interconnection which was a build in feature in the HV2201PJ-G. Secondly, Arduino architecture have built in library (i.e., shiftOut) to handle 8 bit shift register. Apparently, the bit register address can be addressed as numerical value as exchange to binary representation. For example, to turn switch SW0 and SW1, the binary address will be (00000011) which can represent in term of numerical value (i.e., 3) in the coding structure.

None the less, the FES2013 capable of outputting all the parameters as in Table 4-1. The system has adjustable pulse charge (i.e., pulse amplitude and pulse width[4]), frequencies, wave shape[4] (i.e., biphasic and monophasic), and duty cycle (**DC6**).

Similar to EES, FES2013 capable to deliver precise constant current under varying load compared to DS2000 (**DC7**) as discuss in section **5.3**. Previously, Wilson current mirror application was only tested for the tactile stimulation (Kaczmarek et al., 1991; Poletto & Van

[4] Refer section 5.4.2 for the pulse width and wave shape setback.

Doren, 1999). Thus, the usage of Wilson current mirror in this design can probably ensure the current through the muscle is consistent regardless of small changes in impedance due to muscle physiology. This ensure similar consistent physiological activation trigger throughout the exercise regime. Moreover, the DC-DC converter maintain a 200V constant voltage across the muscle (load).

Finally, the design also remove the need of having large magnetic component (i.e. transformer) as well as having very small component count. This make the final design small and portable (DC8). The table in APPENDIX E tabulated all the component used and their order code for easy replication of the design.

Table 5-1 shows the comparison in term of Desired characteristic for EES, DS2000 and FES2013.

Design criteria	EES (Kaczmarek, Kramer, Webster, & Radwin, 1991)	DS2000 (Fornusek et al., 2004)	FES2013
DC1. The FES device was battery powered.	♀	√	√
DC2. Emergency switch button	√	√	√
DC3. Closed loop system	♀	√	√
- Easy coding (for non- advance coder).	♀	♀	√
DC4. Has at least one stimulation channels.	♀	♀	√ *
DC5. Has adjustable pulse charge (i.e., pulse amplitude and pulse width), frequencies, wave shape (i.e., biphasic and monophasic), and duty cycle.	♀	♀	√ **
DC6. Able to deliver precise constant current under varying load.	√	♀	√ ***
- Constant voltage	√	√	√
DC7. Portable	√	√	√
- Low component count.	♀	√	√

Note. Criterion met (√), Criterion not met (♀). *Shorter coding line from HV2201PJ-G daisy chaining interconnection and simple bit addressing. **MATLAB Support Package allow complex mathematical calculation for the FES parameters output. ***Achieved through Wilson current topology.

5.2. Flexible closed loop functional electrical stimulator

From the result, the Arduino Uno can act as intermediate between receiving input from external sensor while output the appropriate FES parameters. Furthermore, the Arduino Uno responded well to the analog value (i.e., voltage) and outputting the intended pulse width and frequency as shown in Figure 4-2.

5.3. Performance comparison between DS2000 and FES2013

5.3.1. Skin model

From Multisim simulation, a model of FES2013 shows below 0.3% tolerance as a result of the output current deviation. Furthermore, FES2013 have minimal output current deviation compared to the design by Han-Cheng, Simpson, Thorsen and Velloso as summarize in the Table 5-2 (Fornusek et al., 2004; Han-Chang et al., 2002; Simpson & Ghovanloo, 2007; Thorsen & Ferrarin, 2009; Velloso & Souza, 2007b). Furthermore, this value theoretically less than the maximum ± 30 % deviation required by BS EN 60601-2-10:2001 Part 2.10[5]

However, the FES2013 through the Wilson current topology did not manage to suppress output current deviation consistently for different intended current and R_{load}. This can be seen the FES2013 shows higher current output deviation starting from 80mA to 120mA and drop when it was 140mA. Nonetheless, the DS2000 also possess similar inconsistency where its

[5] Section 8. Accuracy of operating data and protection against hazardous output. *50.2 Replacement

only able to minimize the mean percentage of current output deviation from 40mA to 100mA and increase slightly from 120mA to 140mA. Yet, Spearmen's rho regression correlation analysis shows no correlation between the intended current and percentage of current output deviation for FES2013 and DS2000 regardless of load introduce. Furthermore, Mann-Whitney Test shows the skin model performance of DS2000 is significantly better compared to FES2013 from the percentage intended current deviation comparison. Despite that, the FES2013 performance might be supress the DS2000 in actual hardware. This might be true through the wide application of Wilson current mirrors in industry (Al-Absi, 2009; Chunhua, Qiujing, & Wei, 2007; Mahattanakul, Pookaiyaudom, & Toumazou, 2001; Wilson, Al-Gahtani, Vosper, & Deloughry, 2006; Zhao, Mao, Li, & Yu, 2011).

Table 5-2 summarize the percentage of output current deviation from several studies.

Author	Percentage deviation (%)
(Velloso & Souza, 2007a)	12[H]
(Han-Chang et al., 2002)	0.5[H]
(Simpson & Ghovanloo, 2007)	0.65[1]
(Thorsen & Ferrarin, 2009)	20[H]
(Fornusek et al., 2004)	0.3[M]
FES2013	0.3[M]

Note: [M] Multisim simulation, [H] Hardware testing, [1] Software simulation as described in (Simpson & Ghovanloo, 2007).

5.4. Cost

Most of electrical component is cheap with the exception of Arduino (RM99.00) and the high voltage DC-DC converter (RM600.00). Although both component represent most of the cost, but they do offer some simplicity and easy handling. Furthermore, the overall cost of FES2013 (i.e., RM 750.00) is much cheaper than commercial FES system (> RM20K).

5.5. Present status report

5.5.1. Resolved

- Che Fornsex, a senior FES researcher together with three application engineer from Maxim and Supertax attested that schematic shown in APPENDIX A . Each component serve its function as shown from the voltage testing along each component except the HV2201PJ-G high voltage switch.

- The Arduino DIN/CLK timing and level was suitable with the HV2201PJ-G high voltage switch requirement as substantiate from scope shot that being provided to Maxim's application engineer as shown in APPENDIX B.

- The digital analog converter from the combination of Arduino and R2R resistor ladder uphold their desired digital analog value. But, it was advisable the resistor to be used was 20k and 10k combination as shown in figure for better output voltage stability.

5.5.2. Unresolved

- Although the schematic and Arduino coding has been validate by application engineer from MAXIM and Supertex, but an actual run on the develop circuit as shown in did not output the expected result. Initially, the objective was to emulate the H- bridge formation where the pair SW0/SW1 and SW2/SW3 switching in alternate manner using the code as in Figure 3-2.

Instead, all the switch (i.e., SW0, SW1, SW2, and SW3) was ON throughout the loop sequence.

- Even if, the HV2201PJ-G high voltage switch did response to a manual switching as provided by the Arduino code in. The objective was to manually change the ON and OFF state of SW0 using user interface. When switch on, the SW0 (i.e., PIN 8) have voltage around 198V when ON and millivolt range if in OFF mode. The coding and schematic as shown in figure 2.1.

- As describe in section 5.1.3, the FES2013 was theoretically capable of outputting wide range of pulse width as well as producing monophasic and biphasic wave form. However, due to the unresolved technical problem as explained above, scope shots on how the pulses look cannot be verified and show in this report.

- At the time of writing, effort still been put to make HV2201PJ-G high voltage switch workable with the Arduino UNO. This effort mainly in controlling the limit on 50 micro second before each transaction.

5.6. Future recommendation

Compatibility between ARDUINO and MATLAB software through the MATLAB Support Package allow more complex FES clinical application research. The required complex mathematical calculation for the FES parameters output can be perform by the

MATLAB, while ARDUINO will act to execute the appropriate command. This is extremely useful for clinical application of FES that more complex in the future.

It is necessary to include the detail about current and voltage waveform, rise time, percent initial overshoot, percentage output current deviation, operational limits, output impedance, linearity and voltage dynamic of range once the hardware completed(Poletto & Van Doren, 1999). A fast rise time is necessary for efficient delivery of a very short pulses. The overshoot should be minimize to minimize physiological significance.

Chapter 6. CONCLUSION

In summary, this report has successfully elaborated the design criteria and technical details of the newly introduced FES2013 for FES research study. All the seven pre-determined design criteria (DC1 –DC7) were explained but not successfully tested in practical situation. The system was theoretically able to supply consistent 0~140mA pulsed current, pulse width of 50 ~ 500 micro second, pulse repetition rate 50 ~ 100 Hz, and functionally monophasic or biphasic pulses. The safe design, having the flexible closed loop FES operating condition capability, easy coding of Arduino Uno and cheaper make the FES2013 ideally suited for research.

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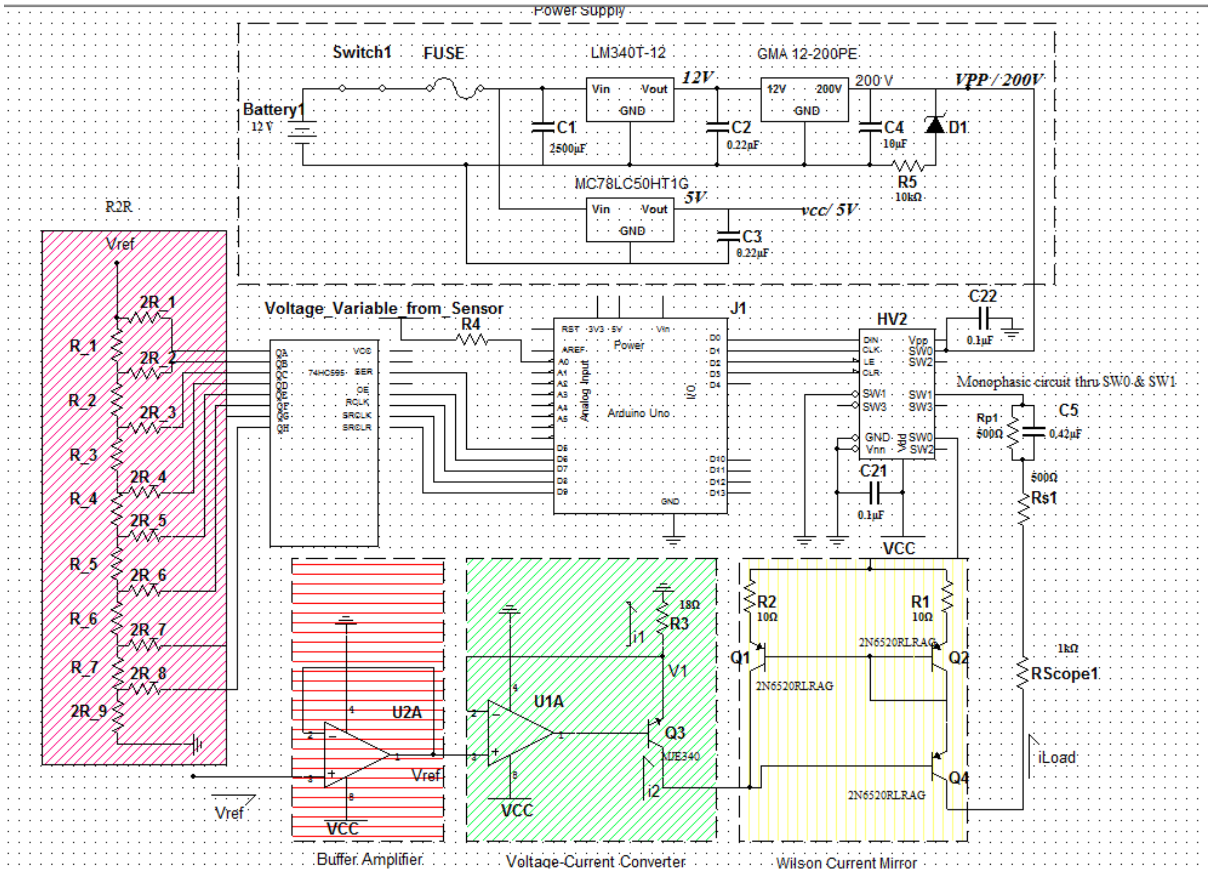
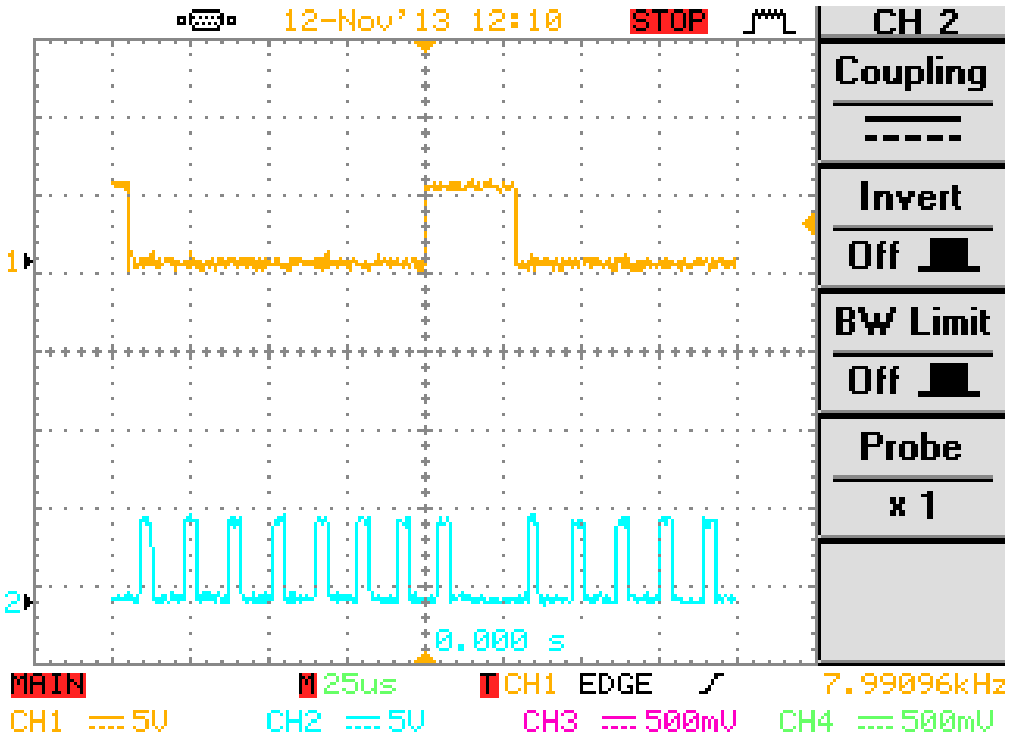
APPENDIX A

Circuit diagram



APPENDIX B

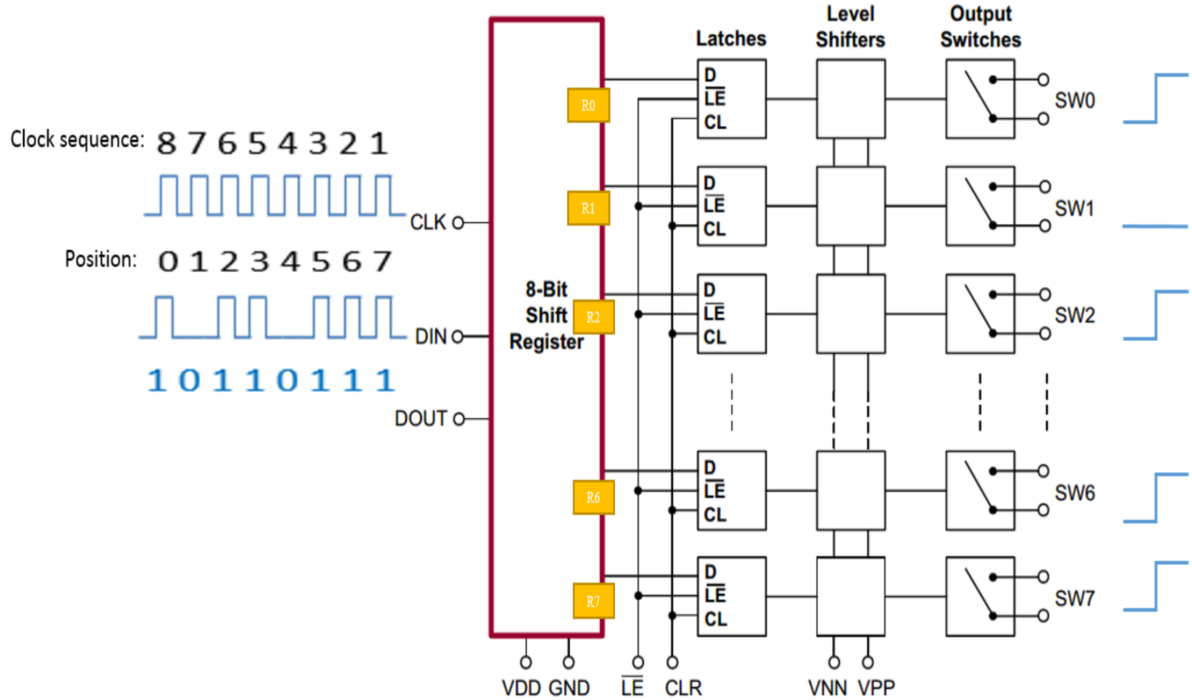


DIN/CLK transactions from the Arduino UNO. Channel 1 = DIN Channel 2 = CLK

APPENDIX C

HV2201PJ-G Working operation

The HV2201PJ-G is an 8 Channels of high voltage analog switch. It work by change the source data from a serial stream to a parallel stream. The 8 analog switch can be control by 3 pins (i.e., Clock: CLK; DataIn: DIN and Latch: LE). The clock set the pace (i.e., electrical pulse) for the data signal and inform the shift register whenever a new bit is sent into the register. Next, the DataIn responsible to send the serial data with the bit (i.e., 1 /0) to determine the on or off of the analog switch while the latch act as gate either enable or disable data transfer into register. Bit shift register receive bit one at a time and hold the register of bits in a memory before latching all the bits all at once. A realistic case scenario where all switch is turn on except switch 1 and switch 2 will correspond to bit sequence of **1 0 1 1 0 1 1 1** as shown in Appendix Figure 1. At instance of 1st clock rise, the bit **1** from position 7 will be transfer into R0 inside the shift register memory (**SRM**). Then, at the 2nd pulse, the bit 1 from position 6 will replace into R0 of SRM, while the bit 1 from the previous R0 shifted into R1 of SRM. The same steps happen on the 4th clock where the bit 0 from position 4 will replace into R0, while R1, R2 and R3 will be occupied by the bit 1 which was shifted from R0,R1 and R2.. Finally, at 8th rising clock R0 will be occupied by the bit 1 from position 0 and R1, R2…R7 SRM will be occupied by a shifted bit from the respective previous register as shown in Appendix Figure 2. Once all bits has been register and store inside the memory, new state of analog switches output were introduce by setting LE logic into low and continue by latch all the bits that shifted in the register all at once. This, thus enable the controlling large number of outputs in the shift register by using few control line on microcontroller. Furthermore, shift register have the advantage where it can be daisy chain one after another and use the same amount of pin to control more than one shift register.



Appendix Figure 1: show the relationship between CLK, DIN and LE pin to control the analog switch output.

SRM / Clock	R0	R1	R2	R3	R4	R5	R6	R7
C1	1							
C2	1	1						
C3	1	1	1					
C4	0	1	1	1				
C5	1	0	1	1	1			
C6	1	1	0	1	1	1		
C7	0	1	1	0	1	1	1	
C8	1	0	1	1	0	1	1	1

Appendix Figure 2: shows how the bit a store and shifted into the next shift register memory at each clock.

APPENDIX D

ARDUINO UNO

Arduino UNO is an open-source electronic prototyping platform which has been used in many educational programs around the world. There are many advantageous of using Arduino. For example, this platform allow designer to easily create prototype without much complication such as in conventional 8051 architecture microcontrollers. Furthermore, since it’s under open source platform, there are plenty of example code to demonstrate the Arduino application. Apart from being inexpensive and cross platform, the Atmel's ATmega328 (16 MHz ceramic resonator) inside the Arduino also can be easily programmed using the Arduino Programming language.

APPENDIX E

List of component used in circuitry

Component	Label	Value	Component selection
Power supply	12V Battery (1.2V x 10)	12V	ENERGIZER – 635429. Minimum current for DC-DC is 500Am. Large current storage allow the FES to be used for multiple time before recharging
	Switch		On-off the system
	LM340T-12		Ensure the voltage is maintained at 12V for GMA 12-200pe power supply. This to ensure no voltage drop whenever the battery is near to deflate.
	MC78LC50 HT1G		Transform the 12V into 5V for Arduino and Wheatstone bridge power supply
	GMA 12-200PR		Convert the 12V input into 200V output voltage
	C1	2500 µF	
	C2 & C3	0.22µF	
	C4	10 µF	
	D1		1N4148.
	Fuse		
Driving stage 1)Wilson current mirror	R1 & R2	10 ohm	Minimize the temperature sensitive of current mirror two resistors (R1 & R2) was added to stabilize the current output.
	Q1 & Q2		2N6520RLRAG
	Q4		2N6520RLRAG
2) Voltage current converter	Q3		MJE340
	R3	18ohm	
	U1A & U2A		MC33202
Pattern generator	HV1		HV2201PJ-G[6]
	Arduino Uno		Description[7]
Feedback controller	Arduino Uno		Description[8]

[6] APPEXDIX C
[7] APPENDIX D
[8] APPENDIX D

APPENDIX F

Continuous current by GMP12-200 HICOM

Continuous current, given The DC-DC converter (GMP12-200 HICOM) with continuous power rating of 1.5W and working at 200V.

$$\boldsymbol{continous\ Current} = \frac{\boldsymbol{Power}}{\boldsymbol{Voltage}} \qquad \textbf{Equation 7}$$

$$7.5mA = \frac{1.5W}{200V}$$

Maximum continuous current

Maximum continuous current for maximum training parameters condition. Given the parameter as (i.e., pulse amplitude: 100mA; pulse width: 500µs; frequency: 100Hz: 75% duty cycle). Therefore,

$$\boldsymbol{Continous\ current} = \boldsymbol{pulseamplitude} * \boldsymbol{pulsewidht} * \boldsymbol{stimulationfrequency} * \& \ \boldsymbol{dutycycle}$$

Equation 8

3.75mA = 100mA * 500 µs* 100Hz* 0.75

Static transfer calculation

Given β = 100, and

$$\boldsymbol{i_1} = \frac{\boldsymbol{v_1}}{\boldsymbol{R_3}} \qquad \textbf{Equation 9}$$

$$\boldsymbol{I_2} = \frac{\boldsymbol{\beta}}{\boldsymbol{\beta+1}}\boldsymbol{I_1} \qquad \textbf{Equation 10}$$

$$\boldsymbol{I_{load}} = \frac{\mathbf{1}}{\mathbf{1+2}/_{(\boldsymbol{\beta^2+\beta})}}\,\mathbf{i_2} \qquad \textbf{Equation 3}$$

Combine (1, 2 &3)

$$I_{load} = \frac{1}{1+2/_{(\beta^2+\beta)}}\left(\frac{\beta}{\beta+1}\right)\left(\frac{v_1}{R_3}\right)$$

$$\frac{I_{load}}{v_1} = \frac{1}{1+2/_{(100^2+100)}}\left(\frac{100}{100+1}\right)\left(\frac{1}{R_3}\right))$$

$$\frac{I_{load}}{v_1} = \frac{0.99}{R_3} \qquad \textbf{Equation 4}$$

Since Q3 have β ≈ 100, and R3 = 18 Ω was chosen so that the maximum pulse amplitude (140 mA**).** Therefore, the resolution for the voltage to current converter is

$$\frac{\boldsymbol{I_{load}}}{\boldsymbol{v_1}} = \frac{\mathbf{0.99}}{\boldsymbol{R_3}} = \boldsymbol{g_m} \approx \mathbf{55}\,\boldsymbol{mA}/_{\boldsymbol{V}} \qquad \textbf{Equation 11}$$

Appendix G

R2R resistor ladder

An 8-bit digital analog converter was achieved using R2R resistor ladder. A total of 256 (2^8) can be produce from a range between 0V and 5V. Although a single chip DAC such as AD5330 is available, but this R2R architecture is easy to build, cheap and can be address easily in Arduino coding. The input for R2R resistor ladder can be control by 3 Pin from Arduino via the manipulation of extended eight 74HC595 output pins.

Appendix H

Coding

```
/*

* Code for making one potentiometer control 3 pulse width 50, 100, 150 microsecond

// INPUT: Potentiometer should be connected to 5V and GND

int potPin = AO; // Potentiometer input connected to analog pin A0

int potVal = 0; // Variable to store the input from the potentiometer

// LED's cathodes should be connected to digital GND

int ledPin = 13;   // LED   connected to digital pin 13

void setup()

{

  pinMode(ledPin, OUTPUT);   // sets the pins as output

}

void loop()

{

  potVal = analogRead(potPin);   // read the potentiometer value at the input pin

  if (potVal < 300)  // Lowest third of the potentiometer's range (0-340)

  {

   for (int n = 0; i < 10; i++)      //Set the pulse to 10Hz per second

    { digitalWrite(ledPin, HIGH);   // set the pulse width to 50microsec by enabling  the LED on (HIGH is
the voltage level)

      delayMicroseconds(50);              // wait for a millisecond
```

```
    digitalWrite(ledPin, LOW);    // turn the LED off by making the voltage LOW

    delay(50);

   }

    delay (1000);

  }

  else if (potVal < 600) // Middle third of potentiometer's range (341-681)

  {

   for (int n = 0; i < 50; i++)    //Set the pulse to 50Hz per second

   { digitalWrite(ledPin, HIGH);   //set the pulse width to 100microsec by enabling  the LED on (HIGH is
the voltage level)

    delayMicroseconds(100);               // wait for a second

    digitalWrite(ledPin, LOW);    // turn the LED off by making the voltage LOW

    delay(100);

   }

    delay (1000);

  }

  else  // Upper third of potentiometer’s range (600-1023)

  {

    for (int n = 0; i < 100; i++)    // Set the pulse to 100Hz per second

    { digitalWrite(ledPin, HIGH);   // set the pulse width to 150microsec by enabling  the LED on (HIGH is
the voltage level)

      delayMicroseconds(150);               // wait for a second

      digitalWrite(ledPin, LOW);    // turn the LED off by making the voltage LOW

      delay(150);

    }
```

```
        delay (1000);
  }
}
```