

ABSTRACT

The invention features a three-phase brushless integrated starter-generator machine used for cranking the internal combustion of the engine and functions as a generator after cranking. The controller for the machine includes a three phase inverter circuit, integrated with battery current sensor for protecting the machine from over current. During motoring, the machine is controlled by using sensorless field oriented control (FOC). The invention basically involves the method of estimating the crank angle from the battery current during cranking and the motor phase voltage zero-crossings.

Figure 1

WE CLAIM

1. An integrated-starter generator (ISG) controller for crank-angle estimation from a Top-dead centre (TDC) position detected during cranking, from a battery current sensor **1** and one or more motor phase voltages **5** to prevent the use of an extra sensor as the current sensor **1** serves as an integral part of the motor drive circuitry, comprising (a) the battery current sensor **1**, (b) a signal conditioning **2**, (c) a three-phase inverter **3**, (d) a microcontroller **4**, and (e) one or more motor phase voltages **5**, wherein:
 - a. The battery current sensor **1** detects over-current production from the ISG controller;
 - b. The signal conditioning **2** rejects switching noise from the sensed current signal;
 - c. The three-phase inverter **3** circuit is equipped with the battery current sensor **1**;
 - d. The microcontroller **4** rejects the noise by digital filtering and detects the TDC from the filtered current signal; and
 - e. One or more motor phase voltages **5** send the signals to the microcontroller **4**.

2. The integrated-starter generator controller of Claim 1 wherein the method of Top-dead centre (TDC) peak detection by battery current sensor **1** comprises steps of:
 - a. Filtering the sensed current through an RC filter **11**, a digital filter **13**, and a peak detection method **16**;
 - b. Converting an analog current signal output of the RC filter **11** to one or more digital values **13** for the microcontroller **4**;
 - c. Performing all operations inside the microcontroller **4** after the RC filter **11**;

- d. Applying an instantaneous speed **16** from the hall-effect position sensor **5** to compensate the filtering delay **15** and provide the angular speed for calculating the offset; and
 - e. Initiating a spark event **17**.
3. The integrated-starter generator controller of Claim 1 wherein the Top-dead centre (TDC) detection logic comprises steps of:
- a. Starting the process **20** by checking if the motor started rotating **21** during cranking; and
 - i. Applying the TDC detection logic **21** when the motor starts rotating **20** during cranking,
 - ii. Digitizing the battery current using Analog to digital conversion (ADC) **12**,
 - iii. Applying the Digital filter **13** to the ADC samples, and
 - iv. Checking if the sample value is greater than the threshold **22**:
 - 1) Checking if any peak occurs more frequent than the no-load speed of the ISG **23** when the sample value is greater than the threshold **22**:
 - a) Rejecting the sample **27** when any peak occurs more frequent than the no-load speed of the ISG **23** for two-stroke engine or when any peak occurs more frequent than half the no-load speed of the ISG for four-stroke engine, and
 - b) Checking if a valid peak is detected **24**, if no peak occurs more frequent than the no-load speed of the ISG **23** for two-stroke engine or when any peak occurs more frequent than half the no-load speed of the ISG for four-stroke engine:

8. The integrated-starter generator controller of Claim 1 wherein during a compression stroke at the TDC one or more peaks in the current correspond to the position of a crankshaft where the torque is maximum and one or more peaks represent the TDC of a piston.
9. The integrated-starter generator controller of Claim 1 wherein the current sensor 1 is hall-effect type sensor.
10. The integrated-starter generator controller of Claim 1 wherein the current sensor 1 is resistive type sensor.
11. The integrated-starter generator controller of Claim 1 wherein the sensed current signal is in the range of 0-5V.
12. The integrated-starter generator controller of Claim 1 wherein the cut-off frequency of the RC-filter 11 is chosen such that there is sufficient attenuation at the three-phase inverter 3 switching frequency, during the TDC detection.
13. The integrated-starter generator controller of Claim 1 wherein the output of the RC-filter 11 is connected to an ADC pin of the microcontroller 4 such that the analog current signal is discretized by the ADC.
14. The integrated-starter generator controller of Claim 1 wherein a further level of filtering is done by the digital filter 13 with linear phase.

15. A method for the crank angle estimation in the integrated-starter generator controller from the TDC position detected during cranking and from the output of the zero crossings of motor phase voltages **5** comprises steps of:
- a. Setting a crank angle, ' α ' **31**;
 - b. Reaching the state S2 when a motor phase voltage zero-crossing signal is received;
 - c. Incrementing the crank angle by the $60/N$ when a motor phase voltage zero-crossing signal is received **32**;
 - d. Converting the state S2 to S1 when crank angle equals θ^0 **31**;
 - e. Generating one or more engine-timing signals with the detected crank angle **30**.
16. The method for crank angle estimation of Claim 15 wherein the estimated crank angle generates one or more engine-timing signals.
17. The method for crank angle estimation of Claim 15 wherein when the engine is running, the crank angle is estimated from the TDC position detected during cranking and from the zero crossings of motor phase voltages **5**.

DATED THIS 6th DAY OF DECEMBER 2013.



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AGENT FOR THE APPLICANT

F9 DEC 2013

ORIGINAL

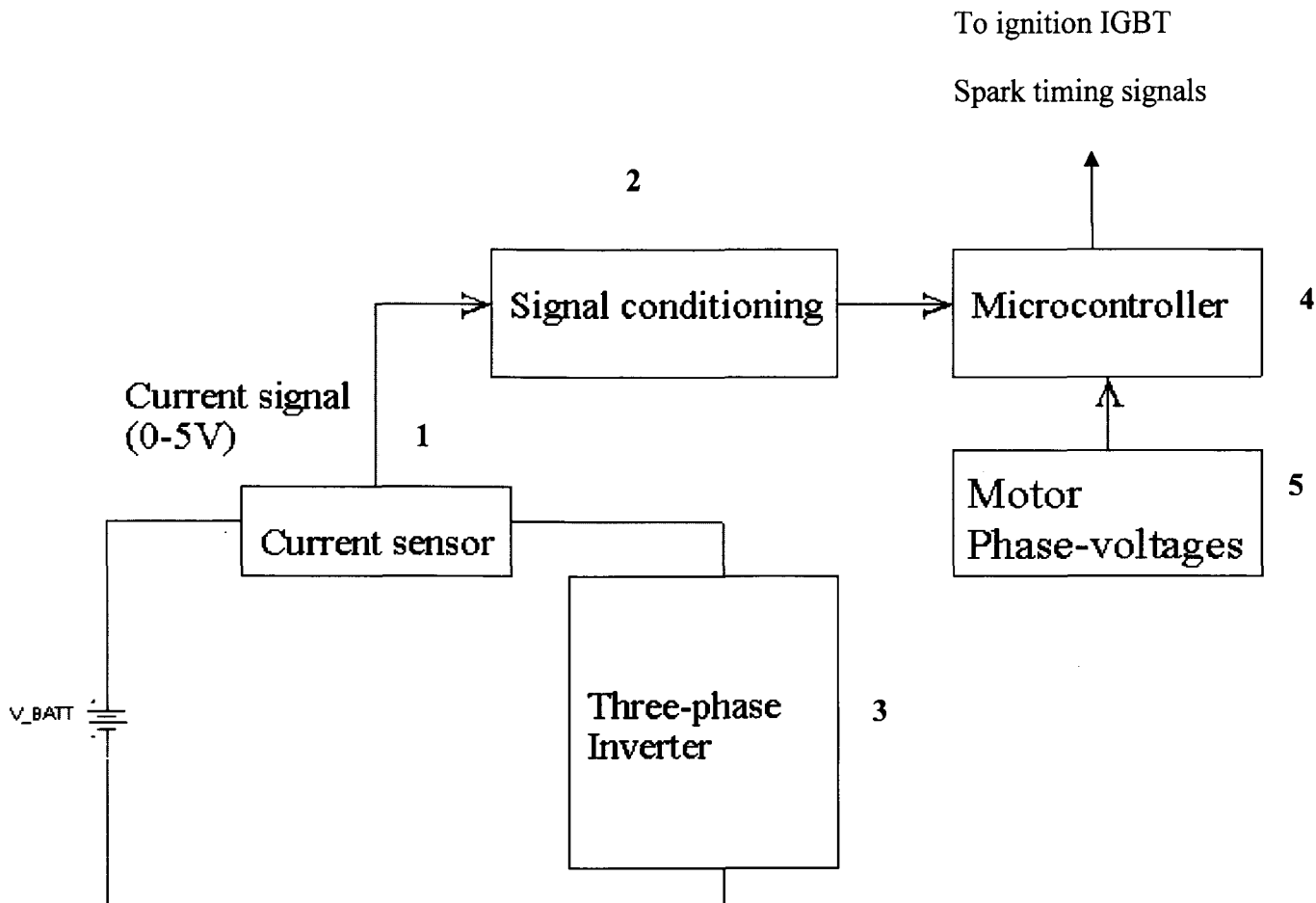


Figure 1

5654 /CHE/ 2013

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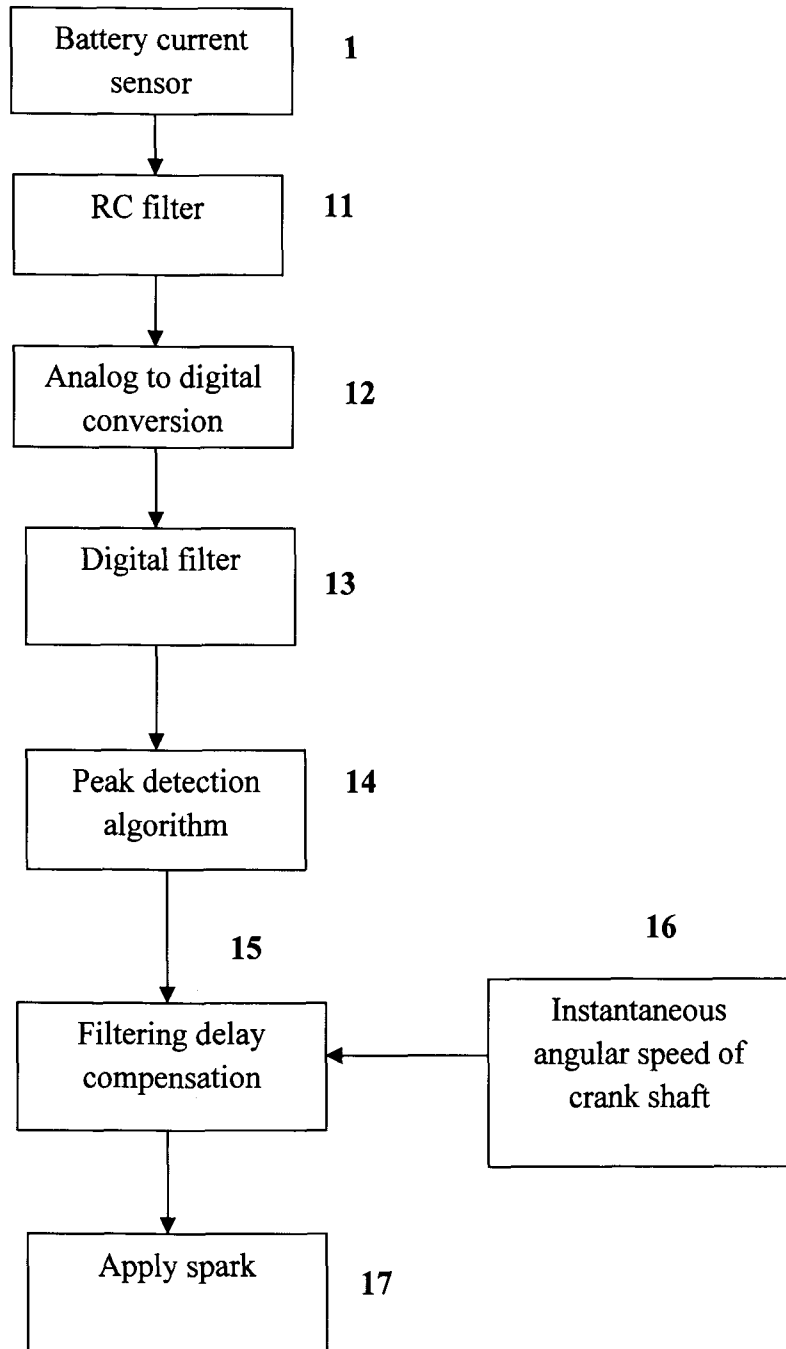
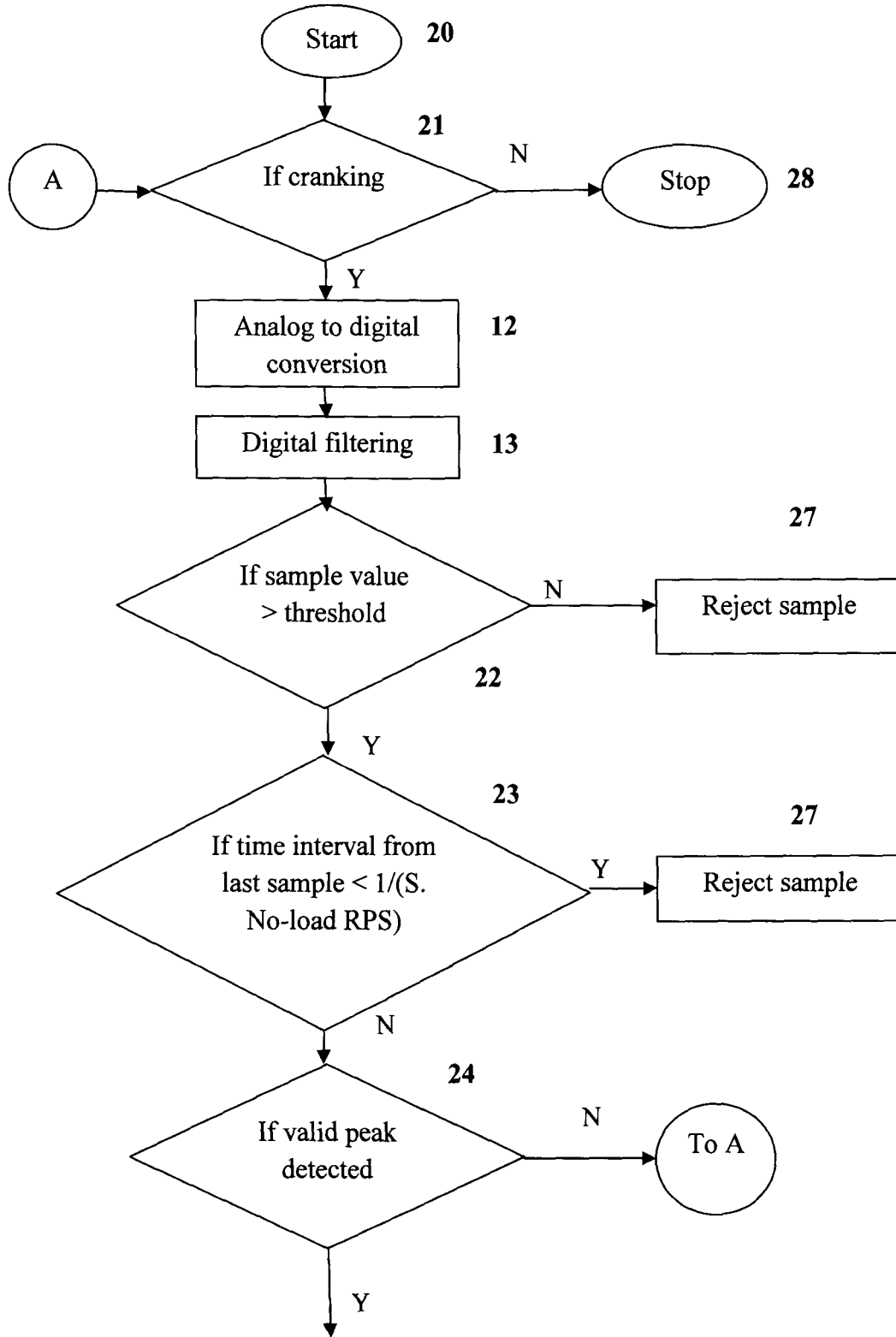


Figure 2

Arunathan
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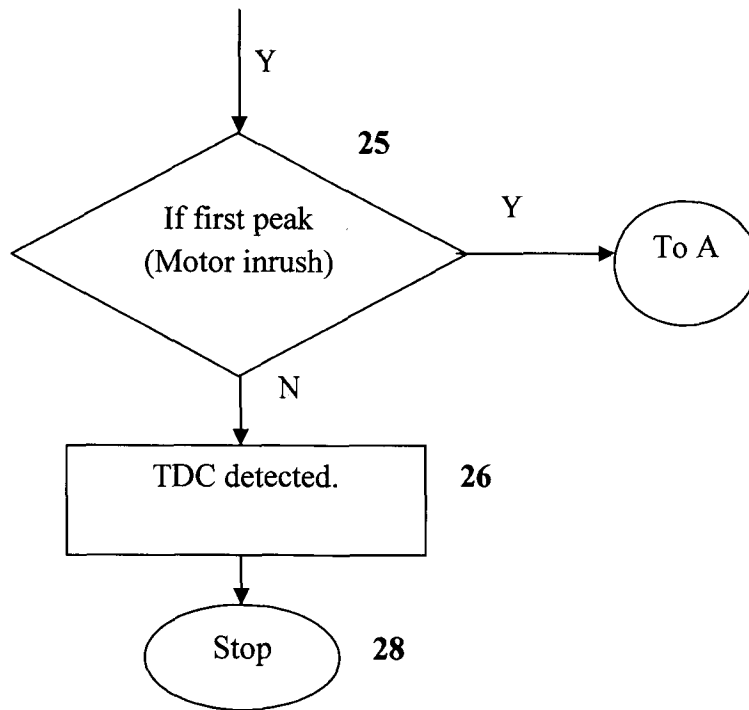


Figure 3

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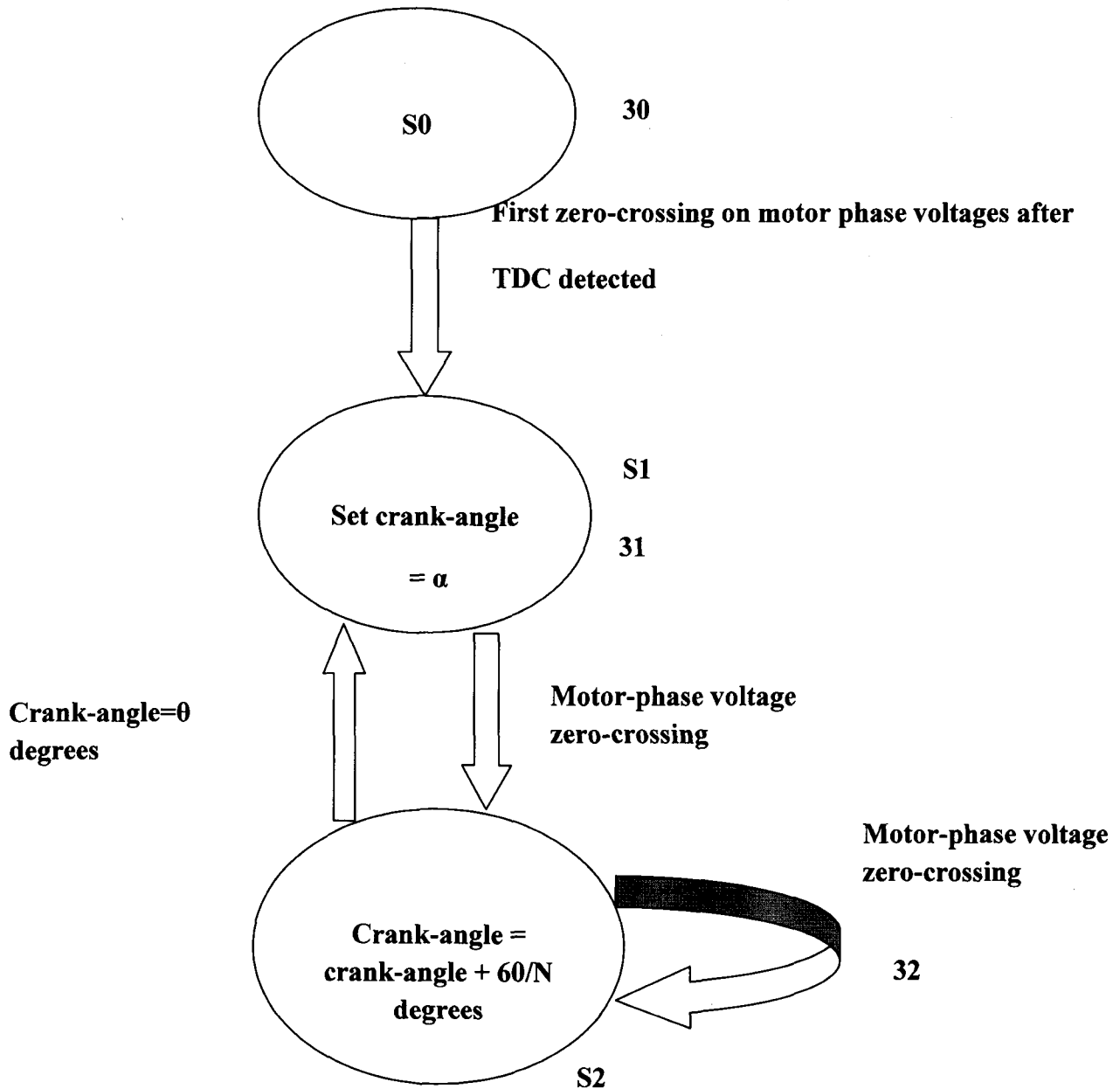


Figure 4

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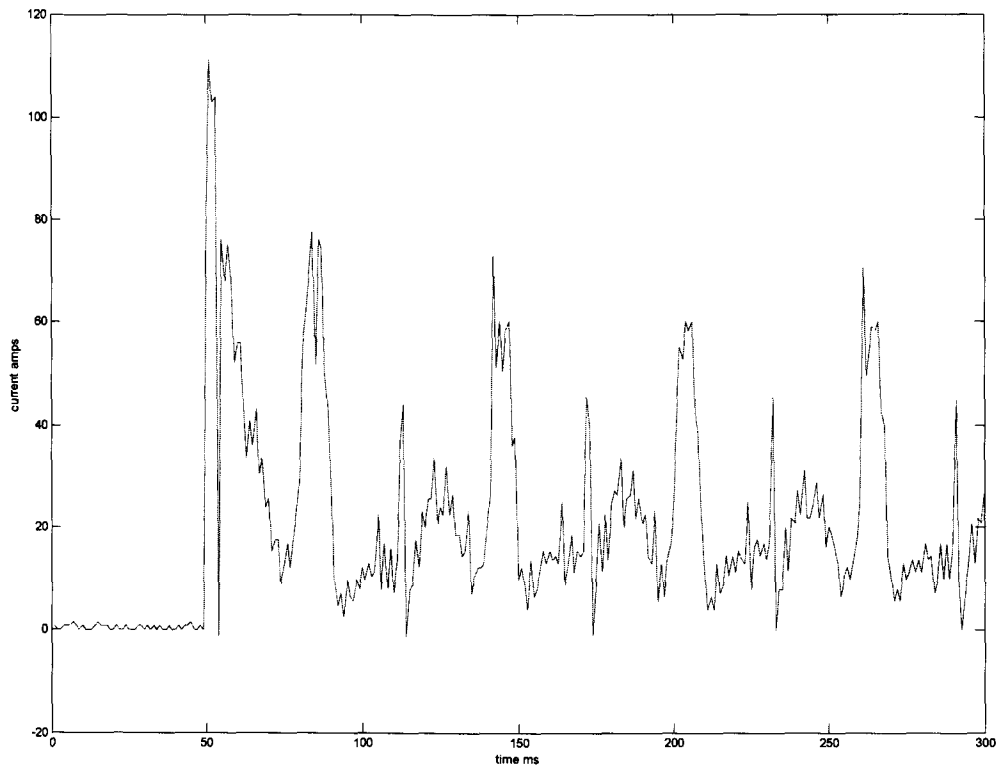


Figure 5

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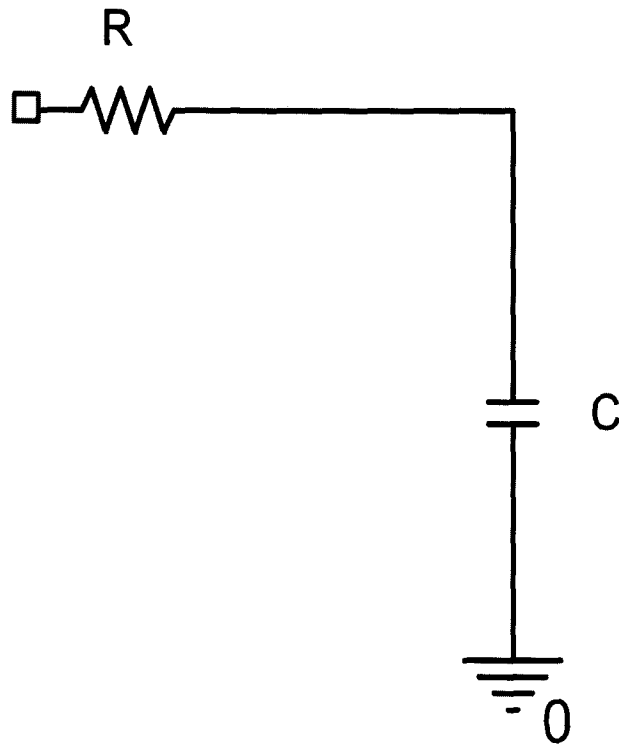


Figure 6

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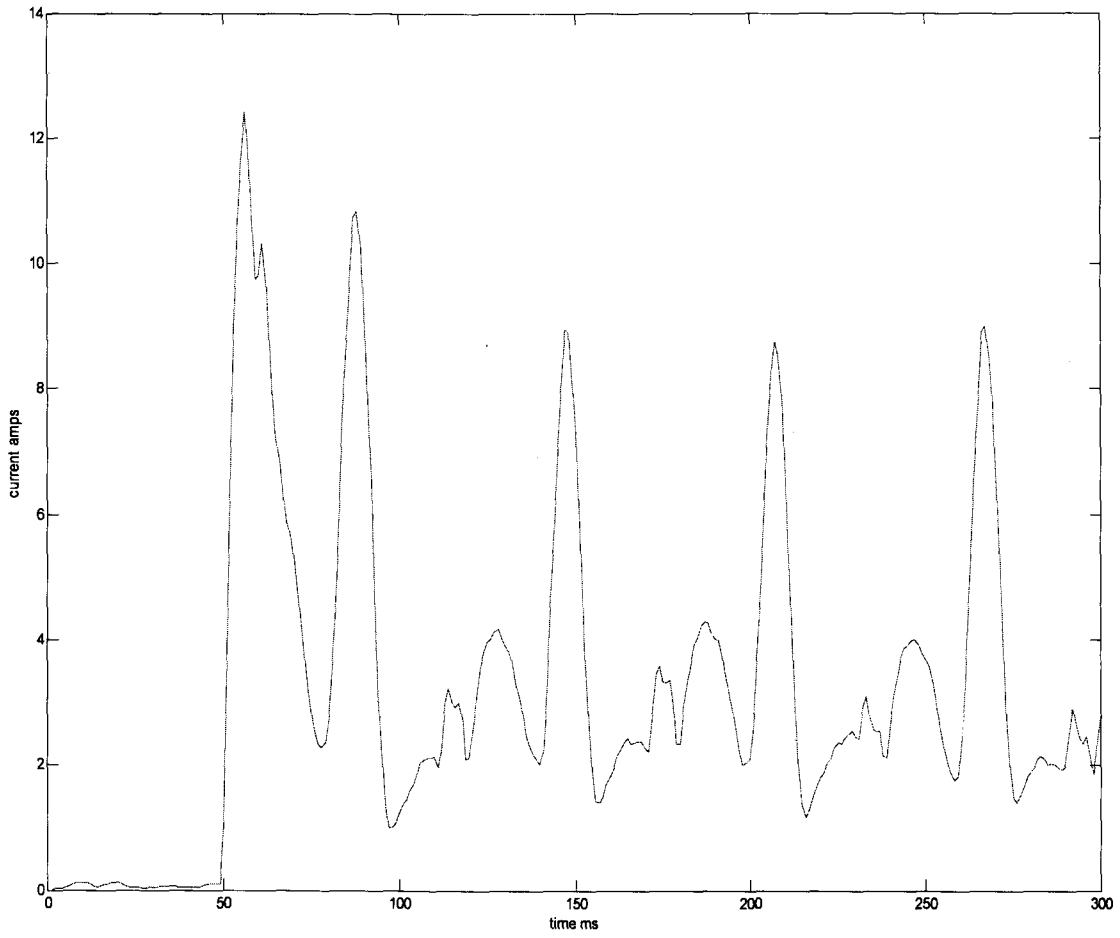


Figure 7

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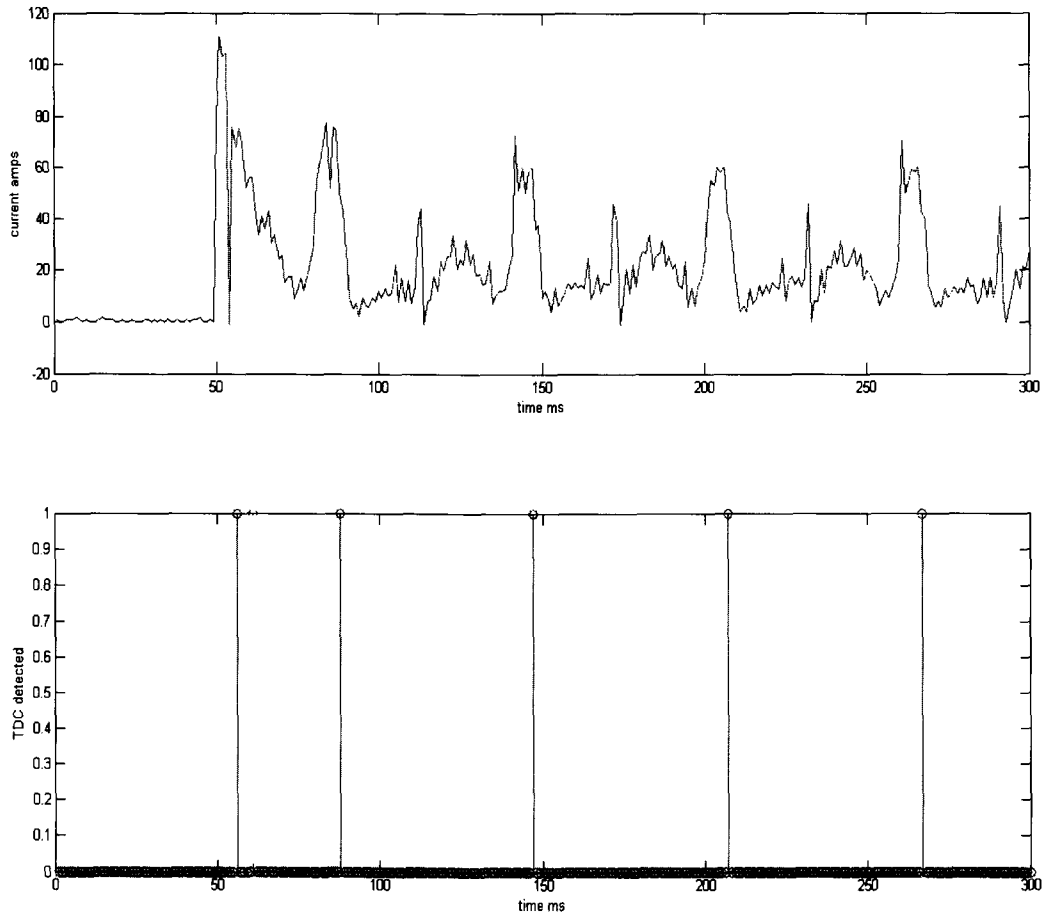


Figure 8

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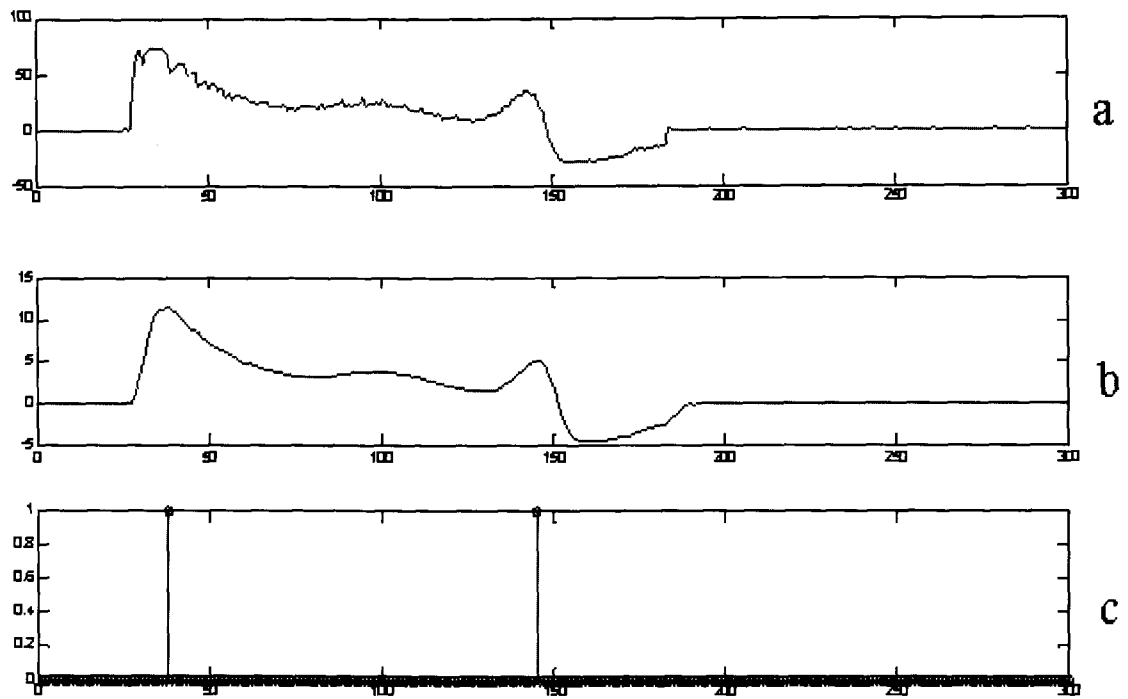


Figure 9

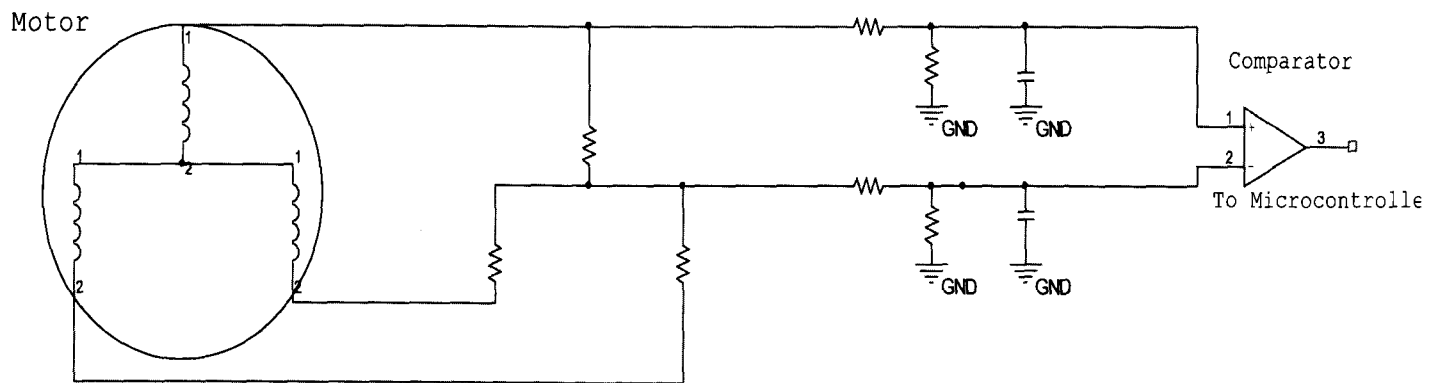


Figure 10

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BACKGROUND

FIELD OF THE INVENTION

The invention features an integrated-starter generator controller with crank-angle estimation from sensed battery cranking current signal and motor phase voltages.

DISCUSSION OF PRIOR ART

The crank-angle in general is determined by (a) measuring the position of the crank angle using an absolute/incremental position sensor and (b) measuring the voltage induced in a coil of generator mounted on the crank-shaft.

EP 1233175 A1 titled “*Starter, start control device, and crank angle detector of internal combustion engine*” describes a starting system for an IC engine which comprises of a brushless starter motor connected to a crankshaft of the IC engine and a starter control for acquiring an absolute angle of the crankshaft. The starter control system executes a drive control of a starter motor and comprises of an ignition reference signal acquiring means, a commutation position pulse signal acquiring means, an absolute angle calculating means and a motor control. The motor control instructing means applies a reverse current such that the crankshaft is temporarily reverse rotated to a predetermined crank position on the basis of absolute angle and is normal rotated for starting the engine. The reference signal generating means produces an ignition reference signal as an output for determining ignition timing of the IC engine. The commutation position signal generating means produces a pulse signal as an output and the crank angle calculating means counts the angle pulse after the electric signal is fed by reference signal generating means as an input and calculates the absolute angle of the crankshaft.

US 5165271 A titled “*Single sensor apparatus and method for determining engine speed and position*” describes a position sensor for determining engine speed as well as engine position. The apparatus comprises of a tone wheel adapted to rotate in sync

with the camshaft and having teeth which are spaced at equal angles, a sensor situated in close proximity of the teeth of the tone wheel and a circuit which is responsive to pulse signals for producing a reference timing signal. The rotating member rotates in sync with the camshaft of the engine. The projections placed at equal angles and the angular projections are detected as they pass a fixed reference location and a pulse signal is produced. A time reference signal is produced when the additional projection and the equiangular projections pass through the reference location and the speed signal corresponding to the speed of the engine in response to the pulse signals are produced.

US 6973911 B2 titled "*Method and device for controlling ignition timing of ignition device for internal combustion engine*" describes an ignition device for an IC engine and a method for controlling the ignition timing of an ignition device. The ignition device comprises of an ignition coil, a generator coil in a high voltage magneto generator, a rechargeable capacitor and a discharging switch element for discharging electric charges. The method comprises of steps of generating a cycle detection signal at an ignition timing calculation start point and preparing an ignition timing calculation signal for determining an ignition timing signal corresponding to calculated RPM. The method also involves generating a peak voltage detection signal at a peak detection point in which a delayed reverse voltage portion of the output voltage has reached a peak voltage generating a start-up voltage detection signal at a start-up point and the start-up voltage is being set to a value for allowing it to stay close to the top dead center (TDC) region of the IC engine. The ignition signal is output to the dischargeable switching element at the time of start-up.

US 20100019507 A1 titled "*Inverter generator*" describes an inverter generator equipped with a generator unit driven by an IC engine, generating alternate current wherein a converter converts the alternate current to direct current and the inverter functions vice versa of the converter. An inverter driver comprises of a microcomputer and drives the switching elements with a PWM signal to make the

alternating current of a predetermined frequency. An ignition unit ignites the engine and the ignition controller controls the operation of the ignition unit. An engine speed detector detects the speed of the engine. The over revolutions are determined by the over revolution determiner. The inverter driver sends a command to the ignition controller to terminate the ignition, to stop the engine when the engine is under over revolution condition.

SUMMARY OF THE INVENTION

This invention discusses an integrated starter-generator (ISG) electrical machine, associated controller and method of estimating the crank angle from the battery current during cranking of the engine and from the outputs of three hall-effect position sensors mounted inside the ISG. The ISG is mounted on the crank shaft. The ISG used in general, is a three-phase brushless machine. During motoring the machine is controlled by using sensorless field oriented control (FOC). An integrated starter-generator (ISG) is used for cranking the internal combustion (IC) of the engine and this assembly works as a generator after starting the engine. The motor drive circuit consists of a three-phase inverter used to drive the ISG as a motor during cranking. The circuitry includes a battery current sensor for detection of over-current production.

In the current invention, the crank angle is estimated from the battery current during engine cranking and the zero crossings of the motor phase voltages. This prevents the use of an extra sensor as the current sensor, which in general is an integral part of the motor drive circuitry. The resolution of the measurement technique is also higher compared to a pulser coil based measurement. The estimated crank angle can be used for producing spark at the required time.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a system block-diagram of the present invention.

Figure 2 shows a signal flow diagram for TDC detection.

Figure 3 shows a flowchart for Top-dead centre (TDC) detection logic.

Figure 4 shows a state diagram for crank angle estimation.

Figure 5 shows the battery current waveform of a starter motor system during cranking when the spark signal is not applied.

Figure 6 shows the RC filter at the output of the current sensor.

Figure 7 shows the output of the FIR digital filter.

Figure 8 shows the TDC positions detected with respect to the sensed battery current.

Figure 9 shows the detected TDC peak by using a method applied to a cranking current waveform with successful engine cranking.

Figure 10 shows the circuit for sensing motor phase voltage zero crossings.

DETAILED DESCRIPTION OF ACCOMPANYING EMBODIMENTS

Figure 1 shows a system block-diagram of the present invention. The motor phase voltages **5** send the signals to the microcontroller **4**. The signal conditioning **2** rejects switching noise from the sensed current signal and the microcontroller **4** detects the TDC from the current signal. The three-phase inverter **3** circuit is equipped with a battery current sensor **1** to detect over-current production during cranking. The current sensor **1** can be either a hall-effect or resistive type. The microcontroller **4** also generates spark timing signals for firing the internal combustion engine.

Figure 2 shows the signal flow diagram for TDC detection. Analog to digital conversion **12** is performed on the output of the RC filter **11**. Analog to digital conversion **12** is necessary to convert the analog current signal to digital values for the microcontroller **4**. After the RC filter block **11**, all operations are performed

inside the microcontroller 4. The TDC peak detected by battery current sensor 1 is further delayed by filtering process such as digital filtering 13 and peak-detection 14. As a result, the detected peak is delayed in time from the actual peak in the sensed current. The digital filter block 13 has linear phase. Linear phase is a property of a digital filter where the phase property of the filter is linear with respect to time (or number of samples). The peak detection process 14 is such that it causes delay of a fixed number of samples. This delay in filtering is compensated by adding an offset to the instantaneous angle at the instant TDC is detected. This is the filtering delay compensation 15. The delay due to digital filtering 13 and peak detection 14 is equal to a fixed number of samples. The sampling frequency is also fixed.

So, the exact delay suffered by the sample as a multiple of sampling time is:

$$d = N/F_s \quad \dots\dots\dots (i)$$

where 'd' is the delay in seconds, 'N' is the group delay due to the digital filter, 'Fs' is the ADC sampling frequency. The offset angle 'α1' due to filtering is given by:

$$\alpha_1 = \omega \cdot d \quad \dots\dots\dots (ii)$$

where 'ω' is the instantaneous angular speed 16 of the crank shaft at the instant the TDC is detected.

This instantaneous speed is calculated from the motor phase voltage zero-crossing signals 5. The time duration between two consecutive zero-crossings can be detected using the microcontroller 4. This time represents the time taken to traverse 60/N mechanical degrees. The instantaneous angular speed is given in this case by:

$$\omega = \frac{11.80}{T} \cdot \frac{100 \cdot N}{\tau} \text{ rad/sec} \quad \dots\dots\dots (iii)$$

where 'N' is the number of pole pairs of the ISG and 'T' is the duration between the two consecutive zero-crossings.

Another offset angle ‘ α_2 ’ is required. Let ‘ t_1 ’ be the time instant at which TDC is detected. Let ‘ t_2 ’ be the instant at which the first zero-crossing is detected after the detected TDC. The angle ‘ α_2 ’ corresponds to the time duration (t_1-t_2).

$$\alpha_2 = \omega(t_2 - t_1), \quad \dots\dots\dots (iv)$$

where ‘ ω ’ is the instantaneous angular speed.

At time instant t_2 , the crank angle is initialised as Crank angle $\alpha = \alpha_1 + \alpha_2$. After the TDC is detected a spark event is initiated at the required crank angle. The instantaneous speed for filtering delay compensation is derived from zero crossings of motor phase voltages.

Figure 3 shows a flowchart for Top-dead centre (TDC) detection logic. The TDC detection logic is applied when the motor starts rotating **21** during cranking; otherwise the process is stopped **28**. The battery current is digitized using Analog to digital conversion (ADC) **12**. Digital filter **13** is applied to the ADC samples. The samples are rejected **27** if their values are lower than a particular threshold **22**. For a two-stroke engine, if any peaks occur more frequent than the no-load speed of the ISG **23**, they are rejected **27**. For a four-stroke engine, if any peaks occur more frequent than the half of the no-load speed of the ISG **23**, they are rejected **27**. The parameter ‘S’ for a two-stroke engine is 1 and for a four-stroke engine is 2. Further if a valid peak is detected **24** and checked if a false peak generates due to motor inrush current **25**. When a valid peak is not detected **24** or when no peak generates due to motor inrush current **25**, the next ADC sample is analyzed when the cranking is still in progress **21**. When a valid TDC is detected **26**, TDC detection process is stopped.

The motor-phase voltages are measured using the circuit shown in **figure 10**. The method depicted in **figure 3** can be used for crank-angle estimation. The estimated crank angle can be used for generating engine-timing signals. The above method can be used with brushless D.C motors.

Figure 4 shows a state diagram for crank angle estimation. The crank angle is estimated from the TDC position detected during cranking and from the zero crossings of motor phase voltages **5**. When a valid TDC is detected as per the logic in **figure 3** the crank angle is set to α . ' α ' would be the offset error if not taken into consideration. ' α ' can experimentally be measured.

Process flow from the condition **S1** and **S2**:

While in state **S1**, if the zero crossings of motor phase voltages **5** is received **31** after TDC detection, crank-angle is incremented by $60/N$ and state **S2** is reached. While in state **S2**, the angle is increased by the $60/N$ when a zero crossings of motor phase voltages **5** are received **32**. State is reset to **S1** when the crank-angle value reaches ' θ ' degrees. **S0** is the starting state **30**.

$$\text{Crank-angle} = \text{crank-angle} + 60/N \text{ degrees} \quad \dots\dots\dots (v)$$

Where '**N**' is the number of magnetic pole pairs on the rotor of the three-phase motor. ' α ' is the angle between the TDC and the zero crossings of three motor-phase voltages **5** after TDC. When crank angle equals θ^0 , the state changes to **S1** and crank-angle is set to ' α ' **31**. The value ' θ ' is 720 degrees for four-stroke engines and 360 degrees for two-stroke engines. The detected crank angle can be used for generating engine-timing signals.

This initial value for the crank angle has two components:-

- a) Angle corresponding to time duration (t1-t2) as mentioned; and
- b) The angle calculated from the 'filtering compensation delay' (α_1).

Figure 5 shows the battery current waveform of a starter motor system during cranking. The spark signal is not applied. So, the engine would not start in this case. The waveform shows peaks. In a DC-motor or three-phase brushless D.C (BLDC)

motor, motor torque is directly proportional to the battery current. Starter motor can be a D.C motor or a BLDC motor.

$$T = k \times I \quad \dots\dots\dots (vi)$$

Where T is the motor torque, 'k' is a constant and 'I' is the battery current. So, the peaks in the current correspond to the position of the crankshaft where the torque is maximum. This is possible only at the TDC during a compression stroke. So, the peaks represent the TDC of the piston.

Figure 6 shows the RC filter **11** at the output of the current sensor. The current is sensed using a sense-resistance or the output of motor phase voltage zero-crossings **5**. The sensed current signal is in the range of 0-5V. For the microcontroller **4** to detect the TDC and reject the noise, some signal conditioning is done **2**. The first level of signal conditioning is an RC-filter **11** at the output of the current sensor. The cut-off frequency of the RC-filter **11** is chosen such that there is sufficient attenuation at the three-phase inverter **3** switching frequency. Also the error due to delay caused by RC filtering process should be acceptable. For example assuming an attenuation of -20dB, the RC-filter -3dB frequency is related to the three-phase inverter switching frequency by,

$$F_s = 10 / (2\pi RC) \quad \dots\dots\dots (vii)$$

Where 'Fs' is the three-phase inverter switching frequency and $1 / (2\pi RC)$ is the RC-filter -3dB frequency.

The output of the RC-filter **11** is connected to an ADC pin of the microcontroller **4** (**Figure 1**). The analog current signal is discretized by the ADC. A further level of

filtering is done using a digital filter 13 implemented in the microcontroller. This filter has the property of linear phase.

Figure 7 shows the output of the digital filter. The logic in **figure 1** can be followed to detect a valid TDC position of the piston. The first peak corresponds to the motor starting current. This peak is not considered.

Figure 8 shows the TDC positions detected with respect to the sensed battery current. The TDC position is detected using the method in **figure 1** with respect to the sensed battery current. The above process of detection of the TDC position can happen only during cranking of the engine.

Figure 9 shows the detected TDC peak by using the method applied to a cranking current waveform with successful engine cranking. **Figure 9a** shows the cranking current waveform. **Figure 9b** shows the output of the digital filter. **Figure 9c** shows the detected TDC peaks including the first false-peak.

Figure 10 shows the circuit for sensing motor phase voltage zero crossings. Once the TDC is detected, the crank angle is estimated from the TDC position detected during cranking and from the zero crossings of motor phase voltages 5. The motor terminals are connected to a star-connected resistive bridge. The motor-phase voltages are measured from the voltages across each resistance of the bridge. The algorithm depicted in **figure 3** can be used for crank-angle estimation.