# FAST ANGULAR SPEED MEASURMENT METHOD FOR ONLINE TRANSIENT STABILITY ASSESSMENT IN POWER SYSTEMS

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## ABSTRACT

Fast measurement of angular speed of rotating machines is a pivotal requirement for many real-time and online power systems applications and, in particular, early fault detection and transient stability assessment and control. This paper presents a new high speed measurement method for computing the rate of change of kinetic energy (RACKE) in real-time. RACKE is an effective criterion for assessment of transient stability in power systems, which was thoroughly investigated using computer simulation. Design and implementation of the proposed speed measurement method is based on a 16-bit microprocessor system and associated hardware circuitry for interfacing an electromagnetic speed sensor, signal conditioning, and control ON/OFF application of a dynamic break to a power system simulator. The operating principle of the developed method is mathematically formulated and implemented using an efficient software algorithm. Implementation challenges relevant to the noisy response of the rotary transducers and fast-speed measurement are also addressed and presented. Performance of the proposed speed measurement method is assessed experimentally using a single machine infinite bus power system. The obtained results and practical observations demonstrated that the speed measurement algorithm is highly accurate (to within approximately 0.013%) with a highly efficient time complexity. This allows for further investigation of RACKE criterion using practical implementation rather than computer simulation.

## 1. INTRODUCTION

The increased dependence of modern societies on electric energy has led to the need for both high service reliability and method of assessing and improving power system reliability. Power system designers, planners and scientists have therefore, always directed their effort towards achieving the maximum possible system reliability at an affordable cost (Basler, 2008). Various events can cause interconnected electric power systems to move from a normal operating state into an unstable state. Depending upon the nature and order of magnitude of the disturbance, stability studies are broadly classified into transient, steady state, and dynamic stability.

The transient stability, which is of particular interest in this paper, is associated with the operation of synchronous machines in parallel, and becomes important with long distance heavy power transmissions. Unlike other types of stability, the time frame of transient stability assessment crisis is the first 1-2 seconds following the disturbance; the system is considered stable, if the machine or the system is found to remain in synchronism within this short time frame. As the transient stability deals with a fraction of a second or so, the operation closer to the stability boundary, and the issue of manoeuvring a system to a more secure operating condition by online stability monitoring and control becomes a critical task. One of the most promising criterion for online transient instability detection is the rate of change of kinetic energy (RACKE) reported in (Al-Azzawi *et.al*., 1999; Zhang *et. al,* 2015; Al-Taee *et. al.*, 2016). This method depends on a single variable, which is the angular speed of the generator. Accurate and fast speed measurement is therefore a key requirement for the practical implementation RACKE criterion.

Fast measurement of angular speed can be considered a critical requirement in many applications including transient stability assessment in power systems (Al-Taee et al., 2016; Al-Taee et al., 2001), real-time stability assessment and speed control (Mellor *et. al.*, 1988; Mellor *et. al.*, 1991; Al-Taee *et. al.*, 2004; Al-Taee *et. al.*, 2006), efficiency optimization of variable-speed drives (Al-Taee *et. al.*, 2011; Al-Din *et. al.*, 2014), and stability assessment and control of single- and multi-area power generation plants (Sattar *et al.*, 2006; Sattar *et al.*, 2008; Sattar *et.al.*, 2001; Sattar *et.al.*, 2002).

Several angular-speed measurement techniques have been reported in the literature; of these, (i) analogue-to-digital converters (ADCs) and (ii) timer/counter are the most common (Gua *et. al.*; 2005). The ADC-based methods treat an angular speed as an ordinary analogy signal. The angular speed is then derived from the sampled data using an appropriate angular speed extraction technique. This category of angular speed measurement method has attracted little interest from researchers in the area of condition monitoring and control. This is mainly due to the large amount of data and relatively low acquiring speed of ADC compared with timer/counter-based methods. The ADC-based methods have been exhibiting their attractive benefits in terms of maximum use of resources of general-purpose data acquisition systems (Arif *et. al*, 2005). In contrast, the timer/counter-based methods treat the signal from an angular transducer as a pulse train. The pulse train is used to start and stop the timer/counter. In order to ensure that the pulse train is at TTL level a simple circuit can meet this conditioning requirement. These methods provide ''instantaneous'' angular speed at single pulse duration. Unlike the ADC-based methods, the timer/counter-based methods can provide high measurement accuracy for low speed and low accuracy for high speed, while pulse-counting-based methods exhibit the opposite accuracy observations. Combined methods, however, provide a well-balanced measurement accuracy over a wide-speed range.

This paper presents the design, implementation and test of a new fast angular speed measurement unit for online transient stability assessment in power systems. The proposed unit is capable of providing instantaneous speed measurements with high-accuracy level over a wide-speed range. Its performance is assessed experimentally through utilizing it for practical implementation of the RACKE criterion. The hardware and software design considerations of the built measurement unit are presented and discussed along with some experimental results.

The remainder of this paper is organized as follows. Section 2 describes the RACKE criterion along with the insertion/removal strategy of a resistive dynamic brake that is used to enhance the transient stability margin of the power system under study. Section 3 describes the hardware design, operation principle and mathematical formulation of the speed measurement unit/scheme. Software algorithm of the power system controller is presented in Section 4. The obtained experimental results are then presented and discussed in Section 5. Finally; the work is concluded in Section 6.

## 2. RACKE Criterion

The effectiveness of RACKE criterion in transient stability assessment was previously investigated, using computer simulation, by several authors (Zhang *et. al.;* 2015; Azzawi *et. al.*, 1987; Azzawi *et. al.*, 1988). When compared to other equivalent direct methods, RACKE requires less computation time since it does not need to solve complex mathematical equations. At any instant of time, the instantaneous value of RACKE (IRACKE) can be obtained from (Azzawi *et. al.*, 1989; Al-Taee *et. al.*, 2001):

$$IRACKE(t) = M\left(\frac{\omega_{(t)}}{\omega_s}\right)\frac{d\omega}{dt} \quad (1)$$

where $\omega_{(t)}$ is the instantaneous angular velocity of the rotor and the momentum (M) can be assumed constant. As a result, RACKE is solely dependent on the measurement of the deviation speed. This simplifies practical implementation of RACKE criterion and significantly reduces the associated computation time.

Among various methods used to improve transient stability margins, the dynamic brake elements have been proposed as an important approach to stabilize a power system following contingencies that cause the system to accelerate. Examples of such contingencies are faults and the loss of bulk transmission lines. Indeed, most contingencies that force the system into a transient stability tend to accelerate the majority of the generators in the power system. In these cases the role of the braking elements is clear; it can be viewed as a fast load injection to absorb the excess transient energy, most of which occurs in the immediate area of the contingency. The main automatic braking elements include; a dynamic braking resistor, a shunt braking capacitor and a dynamic braking resistor in parallel with a shunt capacitor. Previous studies showed that a dynamic braking resistor is one of the effective techniques employed to enhance the transient stability of the power system (Mariotto *et. al.*, 2010). Proper selection of the braking resistor size, insertion time, removal time, and brake location, enhance the transient stability of the power system. The best rate of dissipation is affected by a good choice of the size of the brake. Also the accurate timing of brake insertion and removal leads to a better damping of swings caused by a disturbance. The optimum choice of all factors mentioned above give the greatest possible stability margin (Al-Azzawi et. al., 1989; Al-Azzawi et. al., 2001).

Since the energy dissipated by the brake depends on the period when the brake is inserted in the system, therefore, it is necessary to optimize the period through which the brake is in. Different strategies for insertion and removal of the brake have been reported by numerous authors (Al-Azzawi et. al., 1999; Al-Azzawi et. al., 2001); for brake insertion, authors of these studies investigated the use of fault clearance, depression in electrical power output and drop in machine terminal voltage, the angular velocity or angular velocity in conjunction with angular acceleration, to decide when the braking resistor should be inserted. Concerning the removal of the brake, researchers explored the use of fixed duration strategy, angular velocity and the angular velocity in addition to angular acceleration, as guides to decide removal of the brake. In all these methods the times of insertion and removal instants were not defined precisely (Al-Azzawi *et. al.*, 1988).

As the RACKE method is used to decide system stability, the RACKE criterion is also used to decide the time (Al-Taee *et. al.*, 2016) of insertion and removal of the brake. According to the theoretical studies and experimental findings, the optimum moment of break insertion is achieved at the moment when RACKE just exceeds its maximum negative value. This instant represents the critical clearing time ($t_{cc}$) at which the break should be inserted. This insertion time is found to be effective, since there will be no need to insert the brake if the disturbance is cleared before the critical clearing time, i.e., the system is able to remain stable without the brake. Removal of the brake also depends on the rate of change of kinetic energy of the machine, and its disturbance angular velocity. Figure 1 shows RACKE against time for stable operation. The brake should be inserted at point Bi1 and removed when RACKE passes through zero, point $B_{r1}$ in the figure. At this point, the disturbance angular velocity is zero and changes sign from positive to negative, i.e., it starts to decrease. If the brake had been removed before this point, then the instantaneous angular velocity would still be greater than the normal synchronous speed, and the main purpose of brake is to decrease this abnormal velocity up to a synchronous speed, at which the disturbance angular velocity is zero. If the brake had been left after this point, the angular velocity would have been decreased to a value, which may have led to poor damping of oscillations. Thus, the brake is most effective when removed at this point (Al-Taee *et. al.*, 2001).

Since the dominant factor in RACKE method is the deviation speed of the generator and the time frame of insertion and removal of the brake is around (20ms) therefore a fast and accurate speed measurement system using the microprocessor may be considered as an essential requirement for the practical implementation. A digital speed measurement and control system offers superior performance as compared to the analogue based equivalent systems. In the digital based systems, there is no inherent non-linearity in the speed transducer, the digital signal processing speed can be transmitted over relatively longer distances with no degradation, and the digital system accuracy is not affected by temperature variation and components ageing. The proposed speed measurement method is designed, implemented and tested using a power system simulator that is recently reported (Al-Taee, *et. al.*; 2016), as shown in Figure 2.

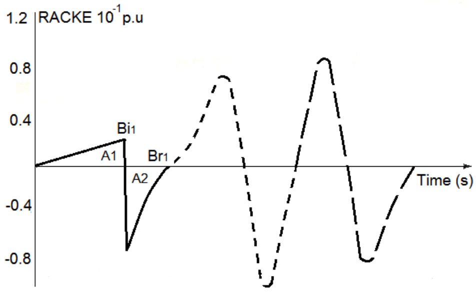


Figure 1. RACKE versus time, with brake for a stable case

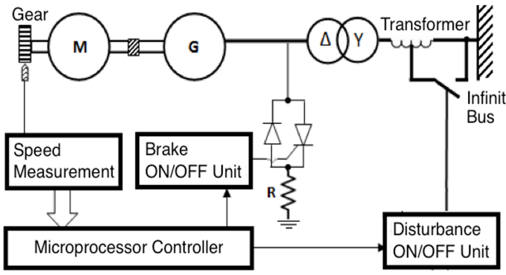


Figure 2. Power system scheme (Al-Taee, *et. al.*; 2016)

## 3. The Proposed Speed Measurement Unit

The hardware circuitry, operation principle and mathematical formulation of the speed measurement scheme are described as follows.

### 3.1 Hardware circuitry

Hardware circuitry of the speed measurement unit comprises a sensing element, signal conditioning circuit and an interface circuit for the microprocessor controller. These elements are described briefly as follows:

*1) Sensing element:* In many engineering applications the transducer that counts a number of generated pulses can be implemented using optical or magnetic incremental encoder (Woolvent, 1977). In the present work, a simple electromagnetic transducer, shown in Figure 3, is proposed and used. It consists of a permanent magnet inside the solenoid, with one end of the magnet terminating in a soft-iron probe. The probe is fixed close to a tooth wheel of ferromagnetic material as shown. This idea is exploited from the fact that the voltage induced in a loop of wire moving through a magnetic field is proportional to the rate of change of magnetic flux linked by the loop. Therefore as a wheel of 50 teeth passes through the probe, the gap length varies and the change in flux density induces an AC voltage signal in the coil of the magnetic pick-up sensor, the output of this sensor requires an additional circuit called signal conditioning circuit.

*2) Signal conditioning circuit:* It shapes the pulses introduced by the magnetic pick up sensor. So that the square wave output of this circuit can drive directly the TTL logic integrated circuit of the speed measuring circuit, and read out unit. The implemented circuit is shown in Figure 4. As illustrated, the circuit consist of a collector comparator LM311, and a positive feedback resistance R3. The effect of this resistance is to make the circuit have two thresholds with the aim of minimizing the effect of the input noise that causes multiple transitions at the comparator's out as the input passes through the trigger point, as shown in Figure 5. The value of R3 is obtained from

$$\Delta V = (R1/(R1 + R3))\,.V_{pp} \qquad (2)$$

Rearranging (2) in terms of R3 yields

$$R3 = (R1.V_{pp}/\Delta V) - R1 \qquad (3)$$

A small "speed up" capacitor $C_1$ of 100 pF is connected across $R_3$ to ensure fast transition. The magnetic pick-up sensor and square wave outputs are shown in Figure 6.

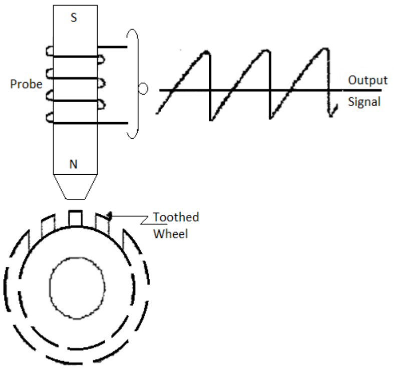


Figure 3. Magnetic pick-up sensor

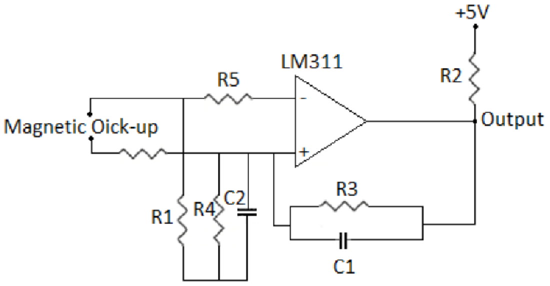


Figure 4. Signal-conditioning circuit

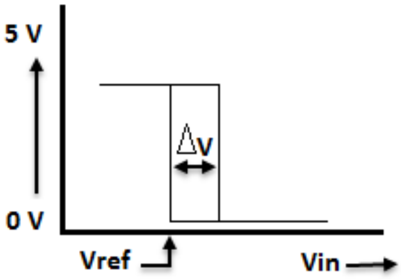


Figure 5. Scheme of the hysteresis

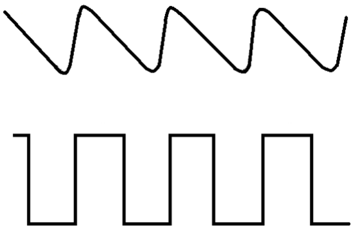


Figure 6. Generation of speed measurement pulses
*Upper:* output of the magnetic pick-up sensor
*Lower:* output of the signal-conditioning circuit

*3) Microprocessor interface circuit:* As shown in Figure 7, this circuit consists of several digital units including (i) mono-stable multi-vibrator (MSMV), (ii) S-R flip-flop, (iii) programmable interval timer (PIT), and (iv) digital-logic gates, as illustrated. The signal-conditioning circuit shapes the tacho-pulses and the MSMV adjusts the width of Tacho-pulses to 1 μs. The output of the MSMV is then applied to the S input of the S-R flip-flop through an AND-gate. The S-R flip-flop is used to enable and disable the counters of the programmable interval timer (PIT), so the count operation will begin and terminate according to the sampling interval of 5 ms.

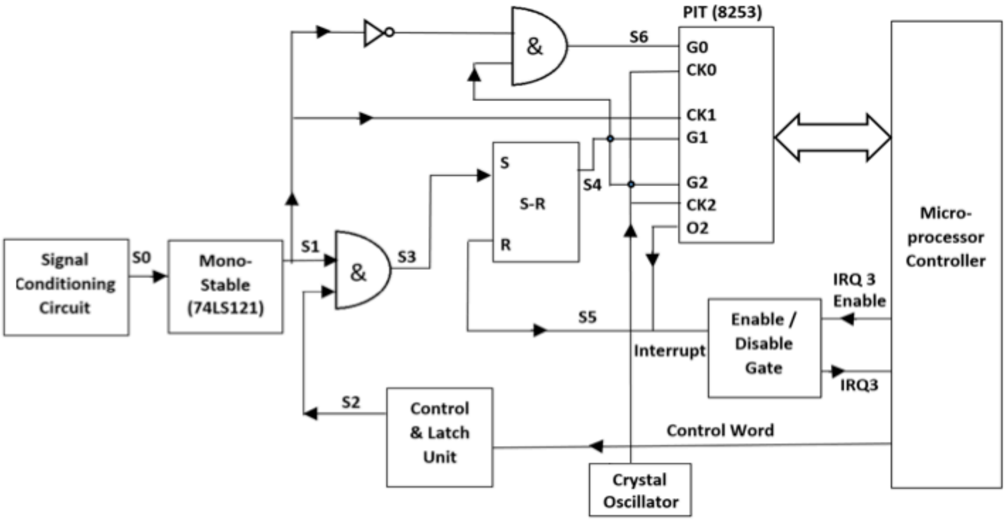


Figure 7. Block diagram of the microprocessor controller interface

3.2 Operation Principle

Operation principle of the proposed scheme can be described with the aid of the circuit diagram of Figure 7 as well as the timing diagram of Figure 8, as follows. Initially, the microprocessor sends a control word to Control/Latch unit, so that the control unit assembles this word and sends a signal as $S_2$ to enable the speed measuring circuit. To synchronize the AND gate's output $S_3$ will be high if and only if both its input becomes logic-1, ($S_1$, $S_2$), this synchronizes the counting operation with the rising edge of a tacho-pulses. The set pulses $S_3$ enable the S-R flip-flop which whenever its output ($S_4$) becomes high, the PIT counters begin the puls-counting operation. The PIT counters are configured for the binary operation, and each one operates as follows:

*1) Counter-0:* operates in the rate generator mode. At the beginning of tacho-pulses, the counter is reset to FFFF Hex., the counter will begin to count down between two successive tacho-pulses. It is thus used to count the clock pulses during the time interval ΔT.

*2) Count-1:* operates in the interrupt on terminal count mode. After this counter is loaded with count value FFFF Hex, the counter will begin to count down if its gate is high. This counter is used to count the tacho-pulses during the sampling interval $T_s$, hence it is clocked by the output pulses train from the MSMV. The counting is disabled by 2-level gate and counter content can be read.

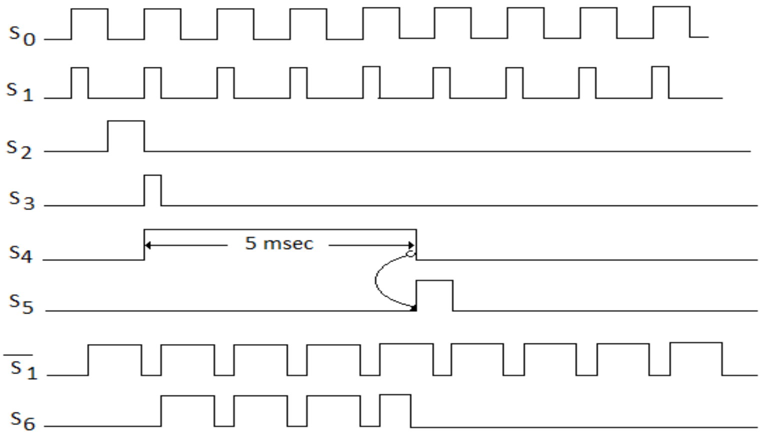


Figure 8. Timing diagram of the speed measurement circuit

*3) Counter-2:* It is loaded with the request number to generate the sampling interval of 5msec or any time to be considered. At the end of 5msec the output of counter2 will go high S5 to reset the S-R flip-flop, which cause to disable all the gates of the counters and terminate the counting operation. Counter-2 output is also connected to the Interrupt Request (IRQ) input of Microprocessor via an enable/disable gate. The purpose of this gate is to enable and disable the interrupt by software program. The IRQ interrupt service routine is used for reading the content of the counters, calculate the speed and do the other tasks related to the speed measuring value.

Since the maximum clock frequency at which the PIT can operate is limited to 2MHz, therefore, a crystal oscillator of 2MHz is configured so that it is output is fed as clock input to counter-0 and counter-2 of the PIT.

The proposed scheme can yield theoretical accuracy of 0.013%, however better accuracy can be realized by using programmable internal counters having higher operating clock frequency.

### 3.3 Mathematical formulation

Principe of speed measurement is illustrated in Figure 9 in which, $T_s$ represents a fixed sampling interval. The integral number of tacho-pulses during the sampling interval is represented by m. Duration of these integral numbers of tacho-pulses corresponds to N clock pulses, the clock pulses during the interval ΔT is denoted by n pulses.

$$n = f_c \,.\, \Delta T \quad (4)$$

$$N = f_c .\, T_S - n = f_c\,(T_S - \Delta T) \quad (5)$$

where $f_c$ is the clock frequency in Hz, and $n$ is the number of pulses during the interval $\Delta T$.

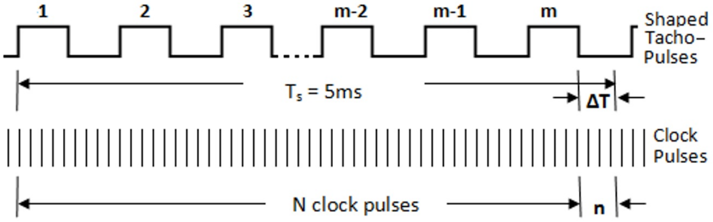


Figure 9. The principles of speed measurement scheme

$$T_S - \Delta \mathrm{T} = \frac{N}{f_c} = \frac{60 \times m}{Speed\ (rpm) \times P} \quad (6)$$

where P is the number of tacho-pulses generated in each revolution. Rearranging (6) yields

$$Speed\ (rpm) = \frac{60\ x\ f_c}{P} \times \frac{m}{N} = K \times \frac{m}{N} \quad (7)$$

where K is a constant dependent on the number gear-tooth and the clock frequency. In the current implementation, the measurement accuracy is found to be around 0.013%, however, better accuracy can also be obtained using a programmable interval timer with higher resolution.

## 4. Software Design

Any Practical implementation based on microcomputer should be based on hardware/software considerations. Software implementation is required to make the hardware part performs its tasks successfully. To control the system during the transient condition, it is required to implement fast program to satisfy the relatively short time frame of transient stability control. Assembly language is commonly used in real time applications, it offers higher execution speed and requires less memory resources when compared to high-level languages. Therefore the assembly language is used to write and implement the entire software algorithms of the proposed system controller. Among various methods used to interface the output devices with microcomputer, the interrupt technique is used to satisfy the present work. So the system simulator can be controlled by the microcomputer. The interrupt technique increases the overall efficiency of the computers system, because it make the external devices request the attention of the processor as needed. The structure of the controller software, written in assembly language, can be divided into a main program and an interrupt service routine.

### 4.1 The main program

The main program can be divided into two parts: the first part initializes the programmable hardware components, stack pointer, interrupt vector address, and memory buffers and pointers. The second part governs background tasks such as reporting and file management. During transient conditions, all acquired and computed values are recorded in data files for further post-processing purposes.

4.2 Interrupt service routine

At the end of each sampling period ($T_s$), an interrupt signal is generated by counter-2 and provided to the interrupt pin of the microcomputer. The interrupt service routine (ISROT), shown in simplified form in Figure 10, consists of three subroutines, namely: speed (SPDROT), RACKE (RAKROT) and brake insertion/removal (BIRROT). The ISROT initially reads a speed sample and calculates the instantaneous deviation ($\Delta\omega$). If the speed deviation is less than some tolerance ($\varepsilon$), the program terminates without action. Otherwise, it calls the RAKROT to decide the necessity of brake insertion/Removal.

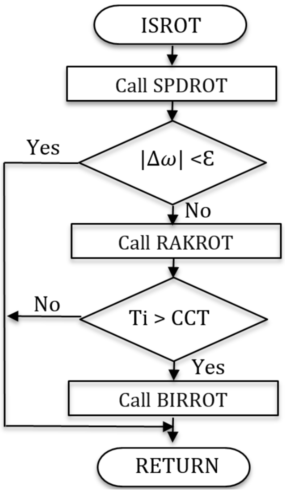
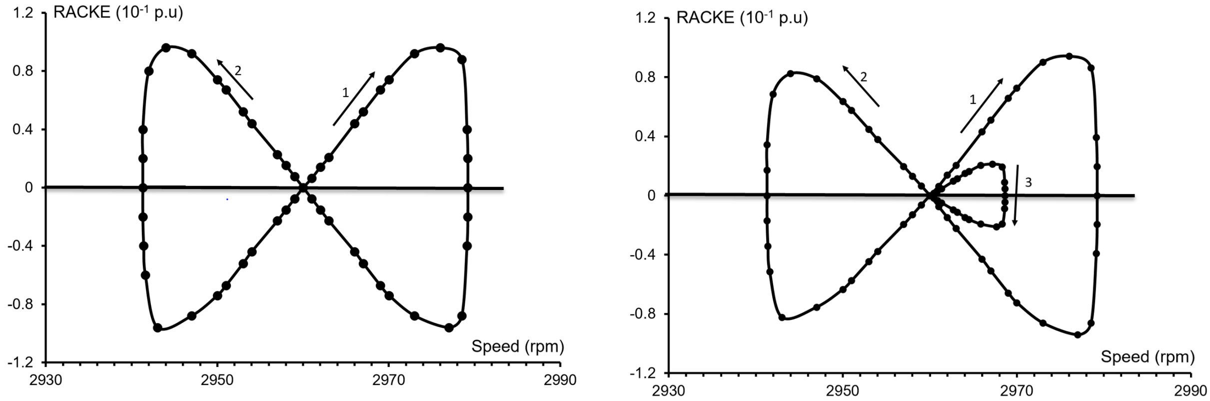


Figure 10. Flowchart of ISROT

## 5. Experimental Results and Discussion

A curve of RACKE against $\omega$ is drawn for a stable condition as shown in Figure 11. It practically illustrates the effectiveness of timely insertion and removal of the dynamic brake. The brake absorbs the excess energy gained by the machine during the transient state and therefore, the energy given up by the generator is increased, leading to better damping of oscillations. The condition for brake insertion is when the disturbance angular velocity is zero and changes sign from positive to negative. Brake removal is that RACKE = 0 and $\omega \uparrow \mp$, where $\omega \uparrow \mp$ means that the variable is zero changing sign from positive to negative. Thus the brake should be removed when the trajectory of RACKE versus $\omega$ passes through the origin. Also it can be noticed that the speed is controlling RACKE.

The effect of brake switching strategy on the fault-clearing times: 230ms where the system is critical stable. Figure 11(a) shows the effect of brake when it is inserted and removed according to RACKE switching strategy. Brake insertion is achieved at the instant when the disturbance is removed from the system, i.e., after 230 ms when the disturbance is occur. Braking removal is achieved according to the conditions mentioned above, in this case is after 290msec when the disturbance is occur. In this case we can notice clearly that system maintain stability very quickly with no oscillation in the machine. However, in Figure 11(b), the brake is removed after 270 ms, which is before the proposed instant (290 ms). The kinetic energy given up by the machine is therefore still greater than that gained during the transient period, therefore the oscillation will take place and the system may lose stability. It can be noticed, in Figure 11(b), that the brake is removed after 270 ms (i.e. before the suggested instant and in this case, the kinetic energy given up by the machine is therefore still greater than that gained during the transient period, therefore the oscillation will take place and the system may lose stability. It can also be notices that a new loop appears in this figure. This loop that represents the energy remained in the system causes a transient instability. These experimental findings confirm the effectiveness of the dynamic brake in damping system oscillations when inserted and removed according to the conditions suggested by the RACKE criterion.



(a) (b)

Figure 11. Effect of RACKE strategy on power system transient stability

a) Brake removal time equals to that suggested by RACKE method
b) Brake removal time less than that suggested by RACKE method

## 6. CONCLUSIONS

The demand for the instantaneous measurement of speed for condition monitoring and control of rotating machines has been increased in recent years. As these measurement units can provide information relating to machine. This paper has reviewed the speed measurement methods. It has also discussed the general process and considerations that ensure effective measurement. Moreover, the used method for the measurement using completely digital measurements units at high speed are achievable by the use of low-price components and low level language technique have then been proposed. The direct ADC method has been implemented. It maximises the use of computing power of a computer to realise a real-time measurement for data. We evaluated in this paper also an improved technique for measuring gear transmission of the generator at high speed, by using high frequency pulses per revolution. The originality of this technique lies in the fact that highly precise. The Practical Implementation of this method shows the effectiveness of this circuit, to enhance transient stability issue.

The problem of transient stability is mainly an instantaneous energy balance problem, the rate of change of energy is a good and fast indication of the power system transient stability, and it is the best way to look at the problem. The rate of change of kinetic energy (RACKE) is at its maximum negative value at the critical clearing time (CCT), later they used RACKE method to build a braking strategy which was shown to have a better performance than other strategies. The RACKE braking strategy uses a single variable measurement, which is the deviation speed ($\omega$), to decide the braking instants. This can be utilized for on-line application of brake switching.

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