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Analysis of Overcurrent Numerical-Relays for Protection of a Stand-alone PV System

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Abstract:

This paper presents an overcurrent protection scheme for a stand-alone PV system consisting of PV array, DC-DC converter, DC-AC inverter, relay and circuit breaker to fed an irrigation load. This scheme is based on a numerical relay which is composed of rms current converter, integrator, comparator, low-pass filter and reset logic. The model of the system is simulated using MATLAB/Simulink. The performance of the relay is investigated at normal conditions, even during motor starting of the irrigation load as well as at faulty conditions. The relay succeeds to discriminate between the fault current and the starting current of the motor and operates only under faulty conditions.

Keywords:

MPPT; Numerical-relay; Overcurrent Protection; PV Array; PWM

1. INTRODUCTION

All recent distribution systems are supported with distributed generators (DGs), which make them no longer radial. Typical DG mainly includes fuel cells, wind-driven generators, small hydro-electric power stations, solar cell arrays, small- and micro-sized turbine packages, *etc*. The application of DGs can reduce the cost of transmission, increase power quality, and easily meet the short-term proliferating power requirement [1]. On the other hand, the interest to utilization of renewable energies and distributed generation results in increasing number of installations not only because of its eco-friendly aspects but also its commercial advantages. Recent distribution systems require more protection options in order to be reliable [2].

Any protection scheme includes circuit breakers triggered by various types of relays such as over-current, over- and under-voltage, over and under-frequency relays, *etc*. All of the relays were traditionally constructed electromechanically and later in solid-state. Currently, digital relays have replaced both types; being faster, compact and reliable in operation ensuring minimum power outage in case of fault. The relays should be directional for distribution systems having DGs [3].

Numerical relays are capable of meeting the fundamental protective requirements such as reliability, sensitivity, selectivity and speed. Therefore, the use of numerical relays will soon replace previous relays' technology such as digital relays, static relays or even electromechanical relays [4].

For the overcurrent protection, the relay operates with or without an intended time delay and trips the associated circuit breakers when the current flowing into the relay exceeds a set-point value. Overcurrent occurs due to presence of faults or overload conditions. For the faults caused by short circuit, the current present may be many times larger than its normal value. Meanwhile, overloads occur if the current exceeding the rated value. These phenomena can cause serious problems because the present of large amount of current may have severe damage to both the faulty part and healthy part of power system [4].

The overcurrent relays (OCRs) have been most commonly used as an efficient device to protect radial distribution systems. In such systems, the OCRs must operate rapidly to minimize fault duration and damage of equipment [2].

Even a short duration of transients in voltage and current may affect the operation of the protection relays. As a result, this will cause the relays to fail-to-trip or mal-trip event to occur. Fail-to-trip occurs when the relay fails to trip in the presence of faults. Mal-trip occurs when the relay trips even though it is in healthy condition [4].

This paper presents an overcurrent protection scheme for a stand-alone PV system consisting of PV array, DC-DC converter, DC-AC inverter, relay and circuit breaker to fed an irrigation load. This scheme is based on a numerical relay which is composed of rms current converter, integrator, comparator, low-pass filter and reset logic. The model of the system is simulated using MATLAB/Simulink. The performance of the relay is investigated at normal conditions, even during motor starting of the irrigation load as well as at faulty conditions. The relay succeeds to discriminate between the fault current and the starting current of the motor and operates only under faulty conditions.

2. SYSTEM DESCRIPTION

Figure 1 illustrates a single-line diagram of a stand-alone PV system feeding a load. It consists of PV system, circuit breaker (C.B.), relay (R) and the load.

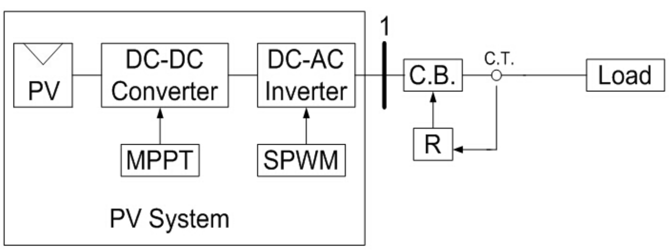


Figure 1. Stand-alone grid.

The system components are described briefly as follows.

2.1 PV System

The PV system is composed of three subsystems; namely, the PV array, the DC-DC converter and the DC-AC inverter.

a. PV Array

The characterization of the PV array is based on the parameters of PV module including open-circuit voltage, short-circuit current, maximum output power, voltage and current at the maximum power point, current/temperature and voltage/temperature coefficients at a temperature of 25?C, and irradiance of 1000 W/m^2. These parameters are listed in **Table 1** for KC200GT PV module. The PV array is composed of several modules connected in series and parallel to meet the load demand through the converter followed by the inverter. The model of the PV module is detailed as reported before [5].

Table 1. Parameters of the KC200GT PV module at 25°C, 1000 W/m^2.

Current at maximum power	7.61 A
Voltage at maximum power	26.3 V
Maximum power	200.143 W
Short-circuit current	8.21 A
Open-circuit voltage	32.9 V
Current coefficient	-0.123 A/K
Voltage coefficient	V/K

b. DC-DC Converter

The DC-DC converter is an IGBT-based-boost converter designed to track the maximum power point of the PV array based on the Perturb and Observe P&O algorithm [6].

c. DC-AC Inverter

The DC-AC inverter consists of 6 MOSFET switches to convert the DC power to AC power. In order to obtain a sinusoidal output voltage, sinusoidal pulse width modulation is used with a carrier frequency equals 27 times the fundamental frequency at a modulation index of 0.9.

2.2 Protective Relay

A numerical relay is designed and simulated to provide over-current protection to the system by giving a tripping signal to a circuit breaker under fault conditions.

2.3 Circuit Breaker

A 3-phase circuit breaker (C.B.) is used to disconnect the load at faulty conditions.

2.4 Load

The investigated load is aimed for irrigation purpose. This is why it includes an induction motor driving a pump to pump deep water to the surface for irrigation purpose. This is in addition to a static domestic load. The motor is rated 10hp, 400V, 0.885 power factor whose initial starting current is 4 times the nominal current. The accelerating period of the motor is 0.2 seconds [7]. The static load is rated 10kW, 0.9 power factor.

3. NUMERICAL RELAY

The principle of operation of the proposed numerical relay is based on the IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays [3, 8]. These equations express a relationship between the value of the fault current and the time setting of the relay.

$$t\left(I\right)=\frac{A}{\left(I/I_p\right)^n-1} \tag{1}$$

Equation (1) takes the form (2) on neglecting ${I_p}^n$with respect to I^n

$$t\left(I\right)=\frac{K}{I^n} \tag{2}$$

where,

I is the relay current,

Ip is the pick-up current, $K=A\ {I_p}^n=contant$

and A, n are constants

With the use of the low-pass filter, the fundamental component of the sensed fault current (I) is extracted and converted to a representative dc value. For a relay current Iexceeding the pickup value I_p, the time setting of the relay is equal to the period elapsed since the fault occurrence until relay tripping. This is obtained by integration of time over that period. In other words, tripping of the circuit breaker C.B. by the relay R takes place when the elapsed period times I^n exceeds the constant $k(I^nt\ \geq k)$ [3].

The logic of the relay operation is outlined in the flowchart of **Figure 2**.

In case the excess of the current Iabove the pickup$I_p$value is temporary; either due to motor starting or any circuit switching action; the reset logic forces the productI^nt to be zero as the it does not reach the k value. The product value remains constant if the current (say motor starting current) decreases below$I_p$with time as the motor speeds up. Subsequently, the derivative of the product is zero and a signal is to be sent to reset the product itself to zero.

4. MODELLING AND SIMULATION

Figure 3 illustrates the model of the proposed stand-alone PV system. It consists of PV system, circuit breaker (C.B.), relay (R) and the load. The model is described in detail as follows.

4.1 PV System Model

a. PV Array

The equations of the model are presented in detail and the model is validated with experimental data [5].

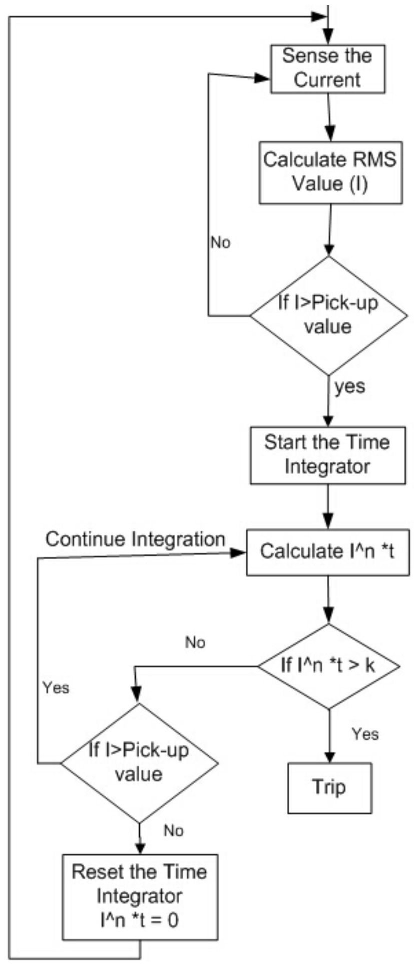


Figure 2. Flow chart of the modeled numerical relay logic.

b. DC-DC Converter Model

A simple boost converter consists of an inductor, a switch, a diode, and a capacitor [6].

c. DC-AC Inverter Model

The DC-AC inverter model consists of 6 MOSFET switches with 2-level PWM generator to convert the DC power to sinusoidal AC power as shown in **Figure 4**. Terminals 1, 2 are the DC side of the inverter and terminals 3 to 5 are the three phase output side

4.2 Overcurrent Numerical Relay Model

The relay model components are shown in **Figure 5** and described briefly as follows per one phase.

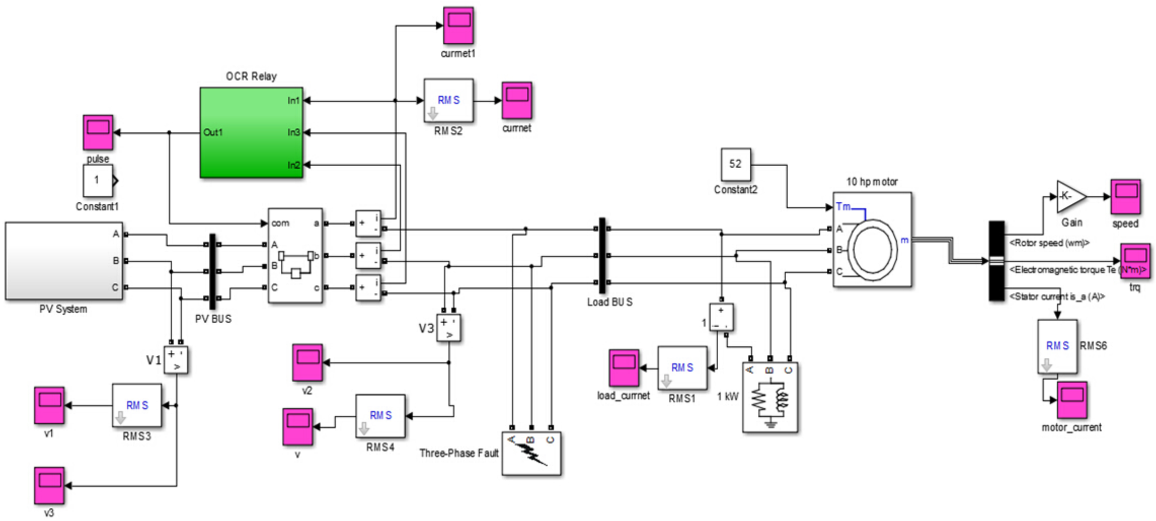


Figure 3. Model of the proposed system.

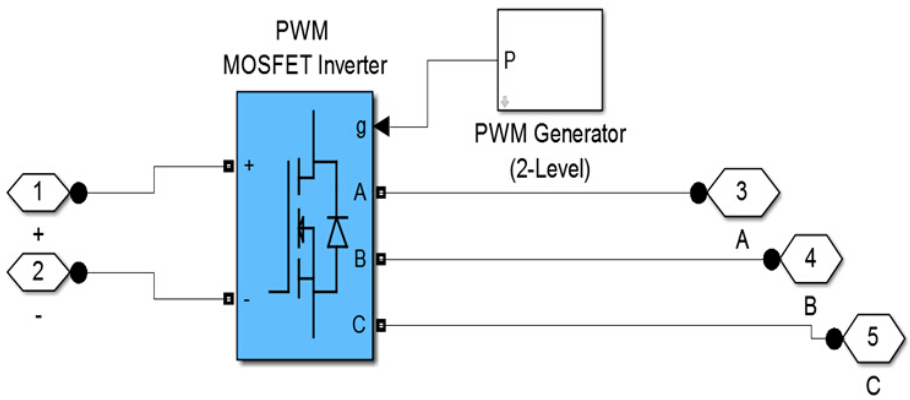


Figure 4. Model of the proposed inverter.

a. Sensing Element

An ammeter is used as a substitute for a sensing element in MATLAB\Simulink to sense the value of the system current as shown in **Figure 3**.

b. Low-pass Filter

The low-pass filter is designed to eliminate harmonics and pass only the 50-Hz fundamental component of the relay current to the converter. The transfer function of the filter is modeled by trial and erroras:

$$T.F = \frac{1}{0.0001s+1} \tag{3}$$

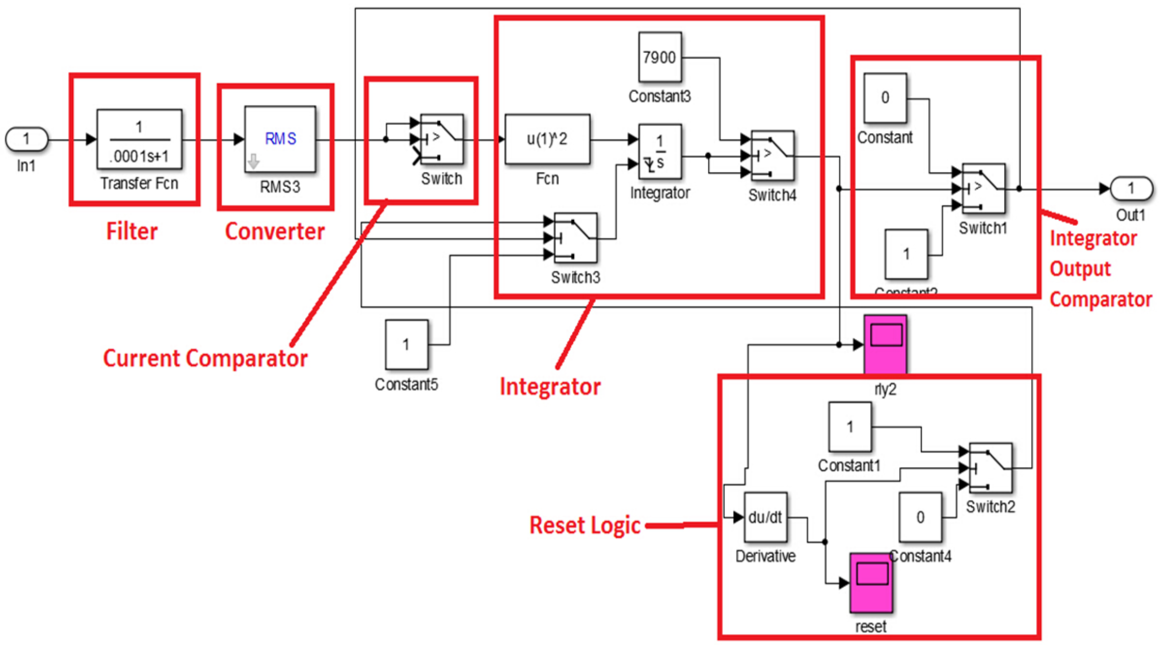


Figure 5. The modeled numerical relay.

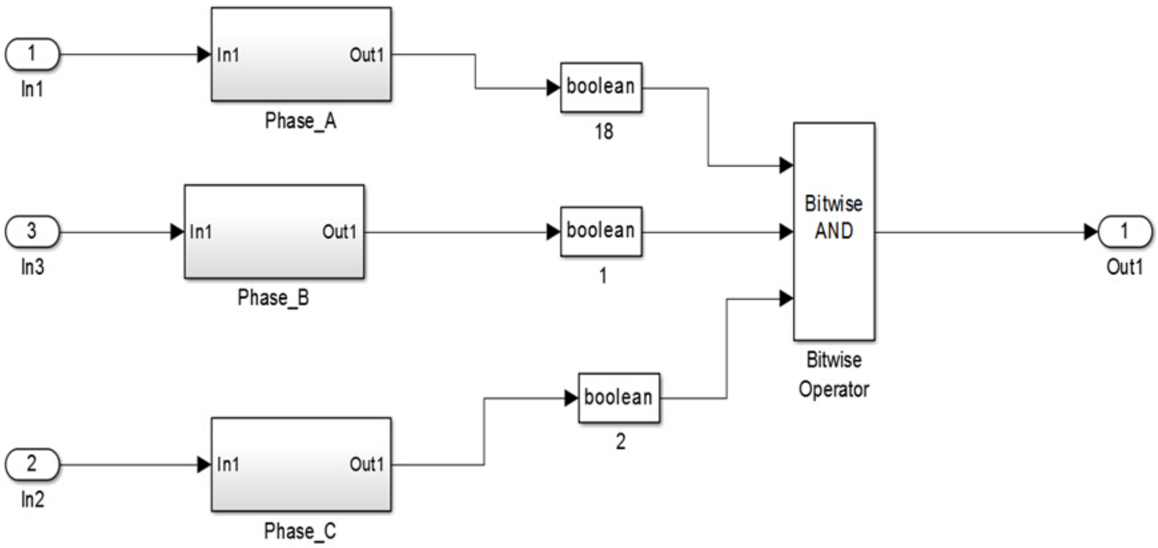


Figure 6. The logic operation of 3-phase numerical relay.

c. RMS Current Converter

The converter is used to determine the rms value of the fundamental sensed current component (I) for comparison against the pick-up value.

d. Current Comparator

This comparator checks if the current Iexceeds the pick-up value $I_p$to give a decision for the relay to send a trip signal.

e. Time Integrator

As long as the current is in excess of I_p, the time integrator keeps rising until the product $I^n t$ becomes equal to the k value, causing the relay to send a trip signal [3].

f. Integrator Output Comparator

The second comparator is used in determining the time settings of the relaythe product $I^n t$ exceeds k.

g. Reset Logic

To reset the time integrator under temporary excess of the current I above the pickup value.

For 3-phase system, the relay components are repeated 3 times. If a fault occurs at any phase, the relay will trip the C.B. using AND logic operation as shown in **Figure 6**.

4.3 Load Model

The load is modeled as described before by a 10 hp induction motor in parallel to a 1-kW static load as shown in **Figure 3**.

5. RESULTS AND DISCUSSION

The relay settings are such that.

a. The pickup current setting I_p allows the load to carry continuous current (*i.e.* 19A r.m.s. or 27 A peak) from the load-flow analysis of the system.

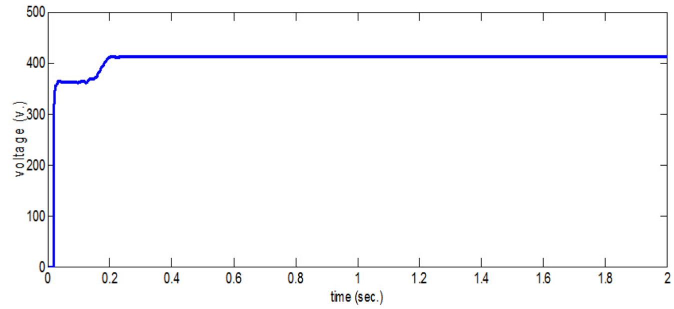
b. Constant k is such selected that any other does not cause false tripping during motor starting as well as transient and switching conditions.

c. Constants A and n are chosen according to the IEEE Standard Very Inverse-Time Characteristic Equations for Overcurrent Relays [8].

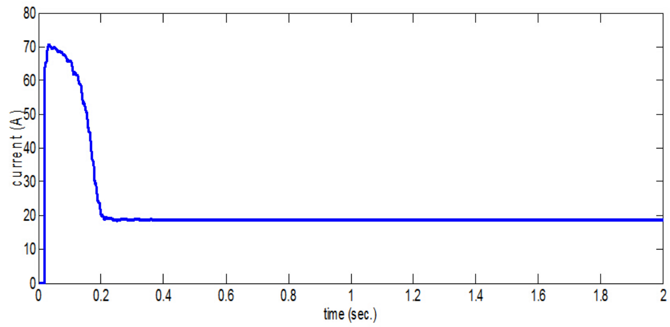
Table 2 shows the settings of the relay.

Table 2. Parameters of the KC200GT PV module at 25°C, 1000 W/m^2

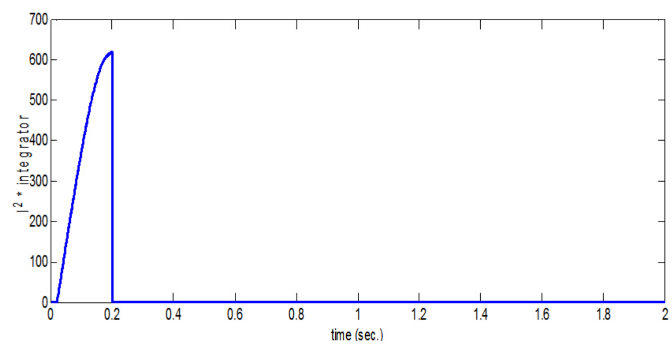
Pick-up current	20 A
Constant n	2
Constant A	19.61
Constant *k*	7850



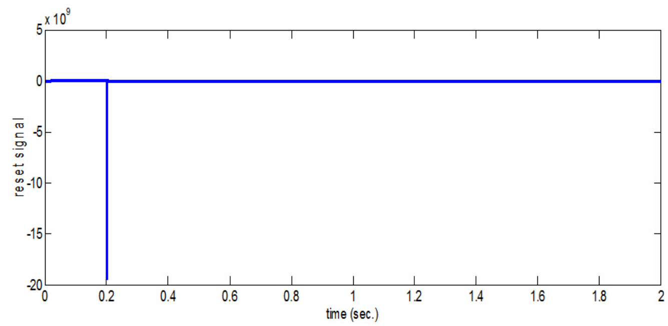
(a) RMS value of the grid voltage



(b) RMS value of the load current

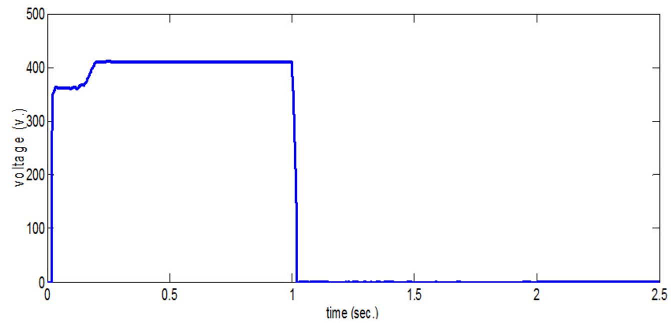


(c) Integrator output

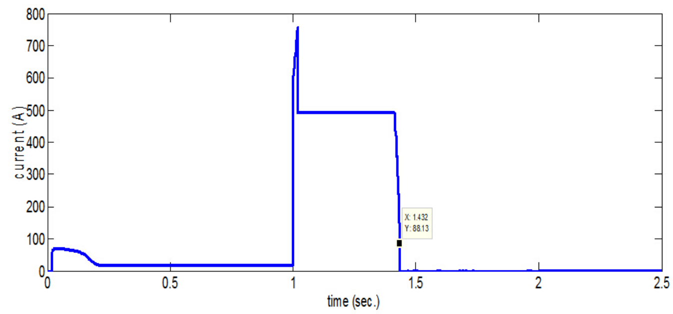


(d) Reset signal of the integrator

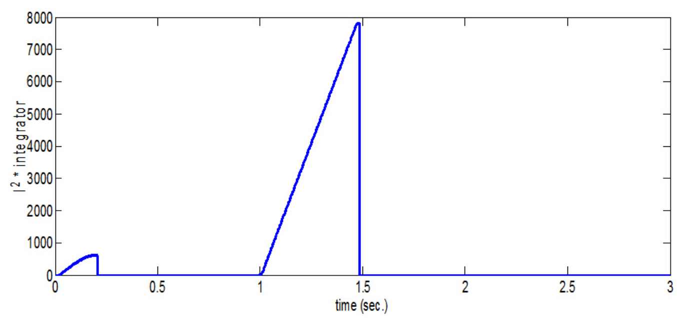
Figure 7.



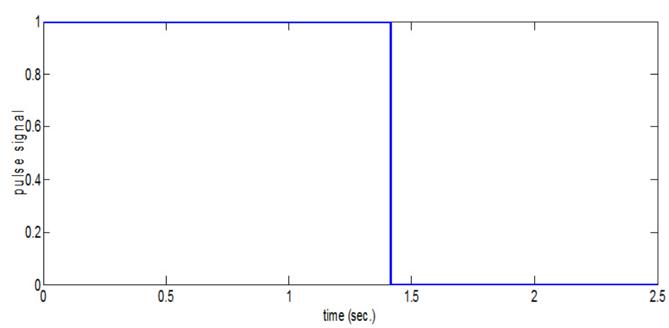
(a) System rms voltage



(b) RMS value of the load current

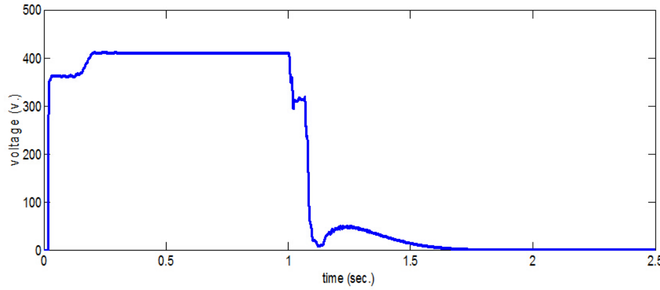


(c) Product output

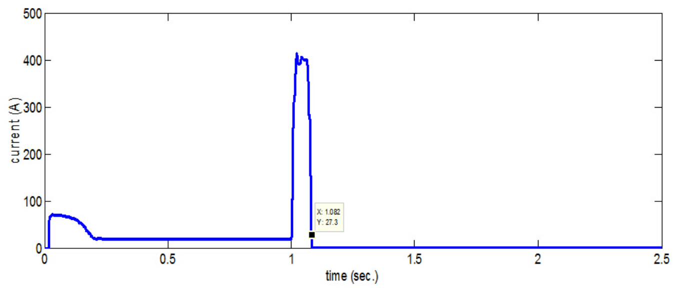


(d) Pulse output to the circuit breaker

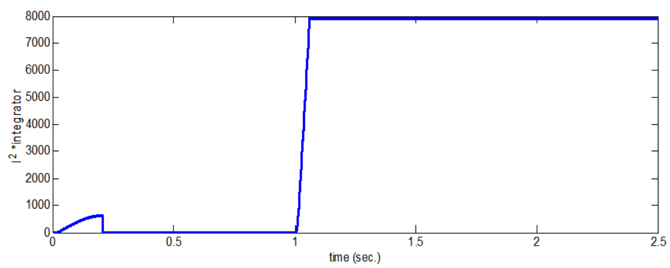
Figure 8.



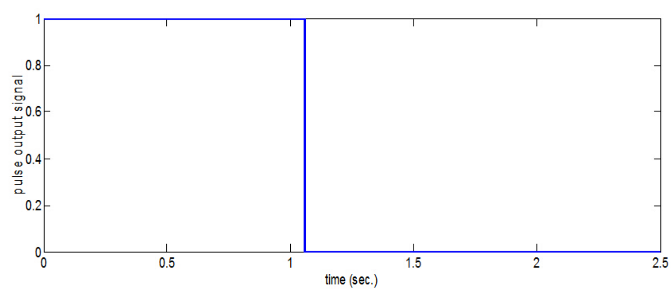
(a) System rms voltage



(b) RMS value of the load current



(c) Integrator output



(d) Pulse output to the circuit breaker

Figure 9.

5.1 Starting of the Motor

During the accelerating period the motor current is above the pickup setting of the relay causing the integrator output to rise. At t = 0.2 seconds, when the motor current falls below $I_p$because the speed up of the motor, the integrator output remains constant. Subsequently, derivative of the output signalis zero which calls for relay reset. **Figure 7** shows: (a) the rms value of the grid voltage, (b) the rms value of the load current, (c) the integrator output and (d) the reset signal of the integrator.

5.2 Three-Phase fault

In this case, a 3-phase fault is applied at the terminal of the load after 1 sec. of operation. The fault remains 2 seconds and then cleared. Once the fault is applied, the integrator output rises until it reaches the value of *k* (7850) causing the relay to trip the circuit breaker after 0.432 seconds of fault as shown in **Figure 8**. **Figure 8** shows: (a) the system rms voltage, (b) the rms value of the load current, (c) the integrator output and (d) the pulse signal to the circuit breaker.

5.3 Single-Phase to Ground fault

In this case, a single-line to ground fault is applied at the terminal of the load after 1 sec. of operation. The fault remains 2 seconds and then cleared. Once the fault is applied, the integrator output rises until it reaches the value of *k* (7850) causing the relay to trip the circuit breaker after 0.082 seconds of fault as shown is shown in **Figure 9**. **Figure 9** shows: (a) the system rms voltage, (b) the rms value of the load current, (c) the integrator output and (d) the pulse signal to the circuit breaker.

6. CONCLUSION

The proposed numerical relay is designed to perform overcurrent protection for a stand-alone PV system. The relay is designed to avoid tripping in transient conditions; such as starting heavy motors, switching and temporary faults. The relay is also tested under three-phase and single-line to ground faults and proves its quicknessin operation. For future work, the relay will be modified to be directional.

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