VOLTAGE RESTRAINT FREQUENCY RELAY FOR ACTIVE USERS OF THE ITALIAN GRID

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Abstract - In industrial facilities, like for example Oil & Gas plants, there is often the need to supply the plant both from internal self-generation (with gas or steam turbogenerators) and also from the National Grid. Although this type of plant is not really a power generation station because it never exports power to the National Grid, it is considered anyway an Active User by the Regulation of the Italian Distribution Company, due to the fact that the power turbogenerators can work also connected to the Grid: as a consequence, a frequency relay is required by the Distribution Company at the point of interface between the National Grid and the industrial facility.
Transient Stability simulations are carried out to understand the behavior of this interface frequency relay in case of short circuit faults occurring internally to the distribution of the industrial Facility and a fine tuning of the frequency relay setting is suggested.

Index Terms — Voltage restraint, frequency relay, active users, MV distribution grid, transient stability, phase faults short circuit current.

I. INTRODUCTION

The Italian Standard CEI 0-16 [1], is the reference to be followed by passive and active users that are interconnected to the HV, and MV (≤ 35 kV and > 1 kV a.c.), networks in Italy.

Indeed, the Italian Authority for the electrical energy and Gas (AEEG) stated that the Annex A70 to the Italian Grid Code [2], must be taken into account by the Standard CEI 0-16: the matter is relevant to the network operation when there is distributed generation and to the new recent scenarios of the Smart Grids.

The novelty of this work consists in highlighting the due importance of performing transient stability calculations for the proper fine tuning of the frequency relay used for the interface between Active User and MV National Grid.

Here after, some important aspects of this standard are first discussed since they will be preparatory for the following numerical simulations by computer program.

A. Definition of Active User

Active users are those provided with any equipment (static or rotating, rated > 10 kW) which converts active energy sources into a. c. electrical energy and which is foreseen to be operated in parallel (even temporarily) with the Network.

Based on this Standard definition, the Oil & Gas Plant which is under analysis in this paper has to be considered an Active User even if there is no permanent export of active power towards the National MV distribution grid.

B. Typical Industrial Electrical Distribution

The electrical distribution scheme of a typical industrial plant, in which a synchronous turbogenerator being driven by a gas turbine is operated in parallel to an external supply grid during normal operating conditions, is shown in Fig. 1: the turbogenerator is operated at 11 kV while the external network of the National Grid is operated at 20 kV.

Main electro-mechanical parameters used for the network modelling are reported in the Appendix.

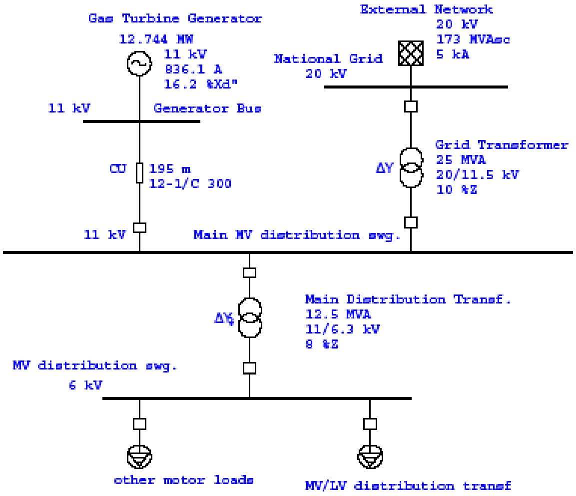

Fig. 1 Scheme of industrial network having internal distributed generation

C. Interface Protection System (SPI) for Active Users

The general configuration for an Active User foresees a General Device (DG) and an Interface Device (DI): the general device provides the main protections for the connected user while the interface device provides the separation of the connected user from the Network in case of abnormal conditions (e.g. faults, frequency transients).

In the Plant being subject of the study, and as also allowed by the Standard CEI 0-16 [1], the two devices can be integrated in a unique device which both protects and separates the user.

The logic scheme of the voltage restraint frequency relay being part of the Interface Protection System (SPI) Device is shown in Fig. 2, while the relevant default relay settings are enlisted in the Appendix.

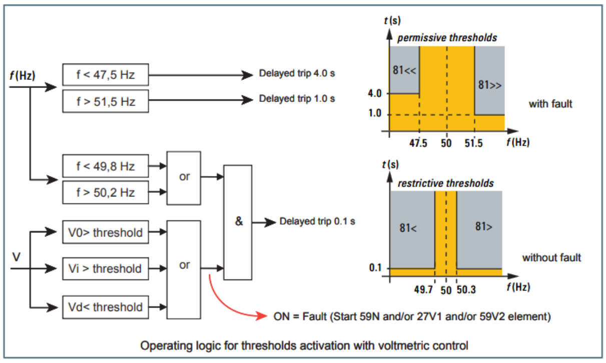

Fig. 2 Logic Scheme of Voltage Restraint Frequency Relay as pe CEI 0-16 Italian Standard

The SPI interface device introduces the use of minimum frequency (81<) and maximum frequency (81>) protection thresholds which are enabled by three different voltage restraint signals on the basis of the type of faults occurring between Network and Active User: the aim of this restraint logics is to distinguish between slow frequency transients and fast frequency transients which could occur in the external Network or inside the internal distribution of the Active User.

The following voltage restraints are used (numerical codes of protection functions are as per ANSI standard [3]):

- 27 Vd (minimum direct sequence voltage) in case of phase-to-phase or three-phase faults. The default setting value is 70% Un (phase-to-phase or phase-to-neutral)

- 59 Vi (maximum negative sequence voltage) in case of unbalanced faults (e.g. loss of phase)

- 59 V0 (maximum zero sequence voltage) in case of phase to earth faults.

The above voltage restraint signals restrict the tripping range normally foreseen for under-frequency (81<) and over frequency (81>) thresholds.

The values of these restricted frequency thresholds are:

- 81> 50.2 Hz (100.4%fn, restricted threshold)
  0.15 s (relay tripping time)

- 81< 49.8 Hz (99.6% fn, restricted threshold))
  0.15 s (relay tripping time)

The frequency relay tripping time of 0.15 s corresponds to a fault clearing time of 0.22 s, considering a typical breaking time of MV circuit breakers equal to 70 ms.

The fault clearing time of 0.22 s is a fixed setting as per a mandatory request by the MV Distribution System Operator (DSO) and it is due to the need of clearing any phase fault occurring in the 20 kV network before the rapid auto-reclosure of the supply is activated in the primary 150kV / 20kV substation which feeds the 20 kV system.

In case of slow transients without faults, the frequency thresholds are kept with a larger setting:

- 81> 51.5 Hz (103%fn, normal threshold)
  1 s (relay tripping time)

- 81< 47.5 Hz (95%fn, normal threshold)
  4 s (relay tripping time)

coherently with what the generators of the Active User can normally withstand according to the reference standards for rotating machines [4], [5] and to the frequency vs. active power droop control during their parallel operation with the Network.

II. NETWORK AND ACTIVE USER BEHAVIOR AGAINST SHORT CIRCUIT FAULTS

Among the several types of faults which could occur, the three-phase short circuit event is considered, which is the most adverse one to assess the transient rotor angle stability of the 11 kV turbogenerator installed inside the industrial facility [6], [7].

The numerical simulation is performed by means of the Transient Stability calculation module of a RMS software [8].

A. Short circuit fault inside distribution of Active User

A three-phase short circuit is simulated at 11 kV of the industrial facility.

The maximum fault clearing time necessary to keep the transient rotor angle stability of the gas-turbine generator resulted equal to 200 ms and this time is compatible with the fault clearing time assured by the protection relays installed on 11 kV system: phase differential (87L) on cable feeders, phase instantaneous overcurrent (50) on motor and transformer feeders.

The resulting frequency oscillation at 20 kV interface point between Active User and National Grid is shown in Fig. 3.

As can be seen, during the three-phase short circuit lasting 200 ms on 11 kV system, the frequency oscillation at 20 kV exceeds the restrictive frequency thresholds 81> and 81< of the SPI interface relay for more than 0.15 s after the occurrence of the fault.

The resulting voltage dip at 20 kV interface point between Active User and National Grid is shown in Fig. 4:

as can be seen, the voltage reaches almost 40% Un of the rated system voltage.

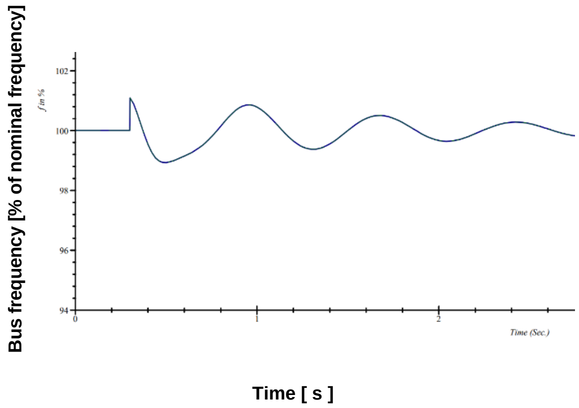

Fig. 3 Transient frequency at 20 kV for a three-phase fault at 11 kV

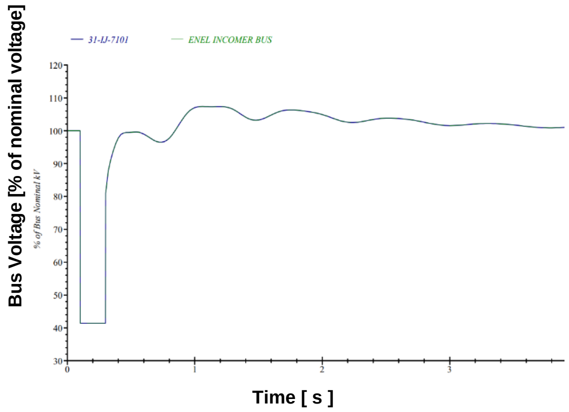

Fig. 4 Transient voltage at 20 kV for a three-phase at 11 kV

If the restraint voltage 27 Vd is kept at the default value of 70% Un, it will set the frequency relay to the restrictive frequency thresholds and the SPI interface relay will trip. This is not acceptable because the transient short circuit happens electrically remotely from the SPI interface relay (there is an interposing impedance between SPI and internal facility distribution given by the 20/11 kV interconnection transformer).

It is therefore necessary to tune the 27 Vd voltage restraint relay to less than 40% Un in order to prevent the activation of the restrictive frequency thresholds thus avoiding undue disconnection of the industrial facility from the National Grid. By taking some margin, a suitable choice can be:

- 27 Vd = 30% Un (restraint positive sequency voltage of SPI interface relay).

B. Protection Logics for faults inside National Grid

In case of any short circuit fault (phase-to-phase or three-phase) occurring inside the 20 kV system and which is electrically close-in (in our case close-in means voltage less than 30%Un) to the SPI interface relay installed on 20 kV point of connection between Active User and National Grid, the Distribution System Operator (DSO) of the National 20 kV system imposes that any MV Active User fed at 20 kV be disconnected by its SPI interface relay before the fault is cleared by the DSO who then restores the voltage supply to the Active User.

Hence, the protection logics imposed on MV network by the DSO is summarized briefly here after:

- a fault occurs in the 20 kV network of the DSO, between the primary 150kV / 20kV substation and the Active User. It is assumed that this fault lasts as a minimum 120 ms causing a 100% voltage dip on 20 kV. The resulting voltage and frequency are shown in the following figures:

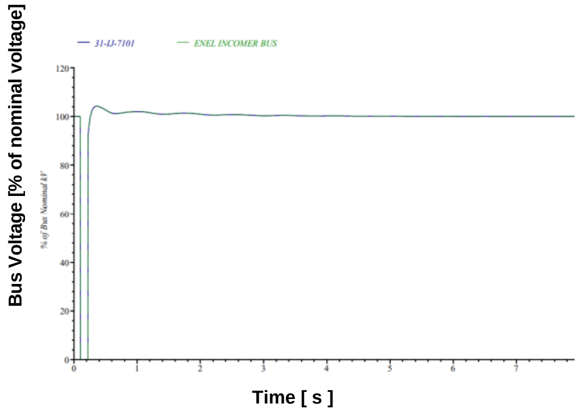

Fig. 5. Transient voltage at 20 kV for a three-phase fault at 20 kV

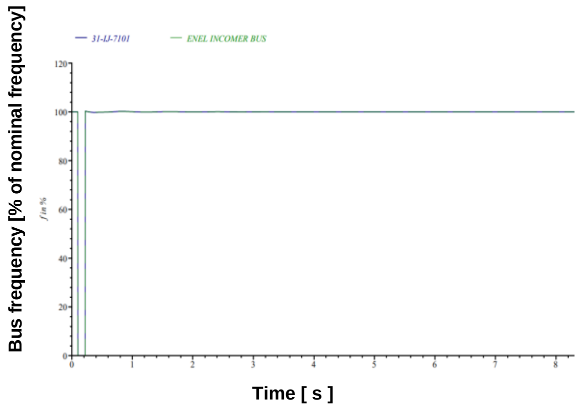

Fig. 6. Transient frequency at 20 kV for a three-phase fault at 20 kV

- The frequency relay 81< internal to SPI interface protection system issues the trip at 150 ms delay from the fault (50 ms pick-up + 100 ms delay), because there is no sufficient time for the frequency relay 81< to reset between 120 ms and 150 ms (drop-out time of frequency relay is 50 ms).

- The SPI interface protection system relay disconnects the Active User within 220 ms (150ms + 70ms) from the fault occurrence.

- In the same time period of 220 ms the fault is cleared by opening the circuit breaker of the 20 kV faulted feeder and at the same time by opening the main incomer circuit breaker on the 20 kV busbar of the 150 / 20 kV primary substation. Thus, after 220 ms from the fault occurrence, all Users fed at 20 kV are de-energized by the primary substation.

- Then, a rapid three-pole auto-reclosure of the main incomer 20 kV circuit breaker takes place at 500 ms after the fault occurrence, and the 150 / 20 kV primary substation re-energizes all the 20 kV feeders.

- The Active User can then be safely reconnected to the National Grid at its 20 kV connection point.

According to the above description, the Active User is disconnected every time a fault occurs inside the 20 kV distribution due to the fact that the primary 150/20 kV substation implements the rapid three-pole auto-reclosure and it is necessary to prevent any out-of-phase reclosure of the supply to the turbogenerators of the Active Users, thus avoiding any electro-mechanical stress and damage to the same turbogenerators.

C. Need of Islanding for the Active User

In the scenario of a short circuit fault event happening in the 20 kV network of the DSO, the Active User is always to be disconnected and its operation shifts to the island condition where the supply to the industrial facility is only given by the gas-turbine generator. The industrial facility has then to be designed to allow for such islanding condition, which means that:

- in case most of the power consumption is already fed by the gas-turbine generator, the generator shall be able to pick-up the remaining load which was fed by the National Grid before disconnection: in our case the gas turbine is designed in order to suddenly pick-up 20% of its rated power at site conditions without undergoing frequency instability, provided that it is pre-loaded to less than 80% of its rated power at site conditions before the disconnection from the National Grid occurs.

- In case the import power from the National Grid is more than 20% of the rated turbogenerator power, a logics of fast load shedding is provided for the 11 kV distribution feeders of the industrial facility in such a way to avoid the trip of the turbogenerator due to underfrequency condition for excessive pick-up of active power.

It is well known that in a power generation station where the turbogenerator exports normally power to the Grid, the turbogenerator is usually designed to withstand the sudden load rejection from the Grid such as to be capable of withstanding the transition from maximum power export to feeding only its auxiliaries in island condition for the temporary time needed before the turbogenerator be reconnected to the Grid. Instead, in the industrial facility which is considered here such a Grid-to-island transition does not exist, because the turbogenerator works only based on specific operating conditions resulting from the process of the Oil & Gas facility.

III. CONCLUSIONS

The Italian Distribution System Operator (DSO) imposes to each Active User, having distributed generation being interconnected to the National MV Network, to use an interface protection system (SPI) device specified by the Italian technical rule CEI 0-16. In particular, the SPI device is equipped with a frequency relay whose tripping thresholds can be restrained by voltage signals. Such a frequency relay is suitable to discriminate between faults which occur internally to the distribution of the Active User as well as faults which instead occur externally to the Active User inside the National MV grid.

Transient stability studies are necessary in order to set the most suitable voltage threshold which can enable the tripping operation of this frequency relay: indeed, a proper setting of the restraint voltage can prevent that the industrial facility be disconnected each time that a phase fault occurs inside the distribution feeders belonging to the same industrial plant.

Anyway, due to the selective coordination of protection relays and to the logics of automation adopted by the DSO on the MV network, in terms of fault clearing times of protections and of rapid auto-reclosure for the automatic restoring of the supply voltage, the same SPI device will disconnect the Active User from the National MV grid each time that a fault occurs inside the same National grid.

For an industrial plant like an Oil & Gas facility the disconnection from the National MV grid could cause sometimes troubles in the scenarios in which the import power from the National Grid is quite significant with respect to the internal distributed generation power and in case no fast load shedding procedures are implemented which could trip some specific users without causing the shut-down of the industrial complex thus preventing the complete loss of production.

For those applications for which it is not acceptable for the Active User to be disconnected from the National MV grid, then it could be preferrable that the industrial facility be interconnected directly to the HV National Sub-Transmission Grid (132 kV or 150 kV for the Italian electric system) where different protection schemes other than the voltage restraint frequency relay could be agreed upon between user and HV Transmission System Operator (TSO).

In future, this work could be further improved by studying also the behaviour during a short circuit fault in case of additional generation by renewables (like for example solar

PV) interconnected by means of power electronic converters to the Network.

V. REFERENCES

[1] Italian Technical Standard CEI 0-16: Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution Company.

[2] Italian Grid Code – Annex A.70: Technical regulation of system requirements for distributed generation, available at www.terna.it.

[3] IEEE/ANSI C37.2: IEEE Standard for Electrical Power System Device Function Numbers, Acronyms, and Contact Designations.

[4] IEC 60034-3: Rotating electrical machines, Part 3: Specific requirements for synchronous generators driven by steam turbines or combustion gas turbines and for synchronous compensators.

[5] IEEE/ANSI C50.13: IEEE Standard for Cylindrical Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and Above.

[6] A. Gomez-Exposito, A. J. Conejo, C. A. Canizares, *Electric Energy Systems – Analysis and Operation*, CRC Press, 2018.

[7] T. A. Lipo, *Analysis of Synchronous Machines*, CRC Press, 2017.

[8] *ETAP Electrical Power System Analysis & Operation Software, www.etap.com*, OTI Corporation, Los Angeles, USA.

VI. APPENDIX

A. Electrical Network Component Data

TABLE A-I
SUPPLY NETWORK

Equipment	Parameters
Equivalent Network at the Interface Point of connection for the industrial plant	20 kV system rated voltage
	50 Hz rated frequency
	173 MVA minimum 3-phase short circuit power
	5 kA minimum short circuit current (sub-transient RMS symmetrical value)
	X / R = 10 Reactance to Resistance Ratio

TABLE A-II
INTERCONNECTION TRANSFORMER

Equipment	Parameter
Interconnection Transformer	25 MVA rated power
	Z = 10% short circuit impedance (referred to rated power)
	20 kV / 11.5 kV Rated voltage ratio
	X / R = 30 Reactance to Resistance Ratio

TABLE A-III
MAIN DISTRIBUTION TRANSFORMER

Equipment	Parameter
Main Distribution Transformer	12.5 MVA rated power
	Z = 8% short circuit impedance (referred to rated power)
	11 kV / 6.3 kV Rated voltage ratio
	X / R = 20 Reactance to Resistance Ratio

TABLE A-IV
PLANT DISTRIBUTION LOADS

Parameter	Value
Rated voltage	6 kV
Total Absorbed Load	10.5 MVA
Lumped Motor Load Modeling	80% motor load, P-Q constant type
Total Motor Load	7 MW
Motor power factor	0.85 lag (average value)
Motor Locked Rotor Current	6 per unit (average value)
Lumped Static Load Modeling	20% static load, constant impedance type (lighting, heaters, uninterruptible power supply systems)
Total Static Load	2 MW
power factor	0.98 lag (average value)

TABLE A-V
TURBO-GENERATOR

4-Pole Synchronous Generator driven by a Gas Turbine	
all reactance and resistance p.u. (per unit) values are referred to the base power Sb = 15930 kVA	
Parameter	**Value**
rated power	15930 kVA
rated power factor	0.8
rated voltage (r.m.s.)	11000 V (line to line)
rated stator current	836 A
rated angular speed	157.1 rad/s
rated no-load field current	274 A
armature resistance	Ra = 0.0027 p.u.
d–axis synchronous reactance	Xd = 1.53 p.u.
q–axis synchronous reactance	Xq = 0.67 p.u.
d–axis transient reactance (un-saturated value)	X’d = 0.267 p.u.
q–axis transient reactance (un-saturated value)	X’q = 0.267 p.u.
d–axis sub-transient reactance (saturated value)	X”d = 0.162 p.u.
q–axis sub-transient reactance (saturated value)	X”q = 0.243 p.u.

leakage reactance	Xl = 0.118 p.u.
zero sequence reactance	Xo = 0.06 p.u.
negative sequence reactance	X2 = 0.211 p.u.
transient d-axis open circuit time constant	T'do = 6.759 s
sub-transient d-axis open circuit time constant	T"do = 0.039 s
sub-transient q-axis open circuit time constant	T"qo = 0.102 s
moment of inertia of generator + turbine + gear	J = 4653 kg m^2
total inertia time constant	H = 3.6 s

B. Modeling of Excitation System of Generator

TABLE B-I
GENERATOR AUTOMATIC VOLTAGE REGULATOR (AVR)

Parameter	**Value**
K_P AVR proportional gain	40
K_I AVR integral gain	30
K_D AVR derivative gain	6.7
K_A AVR actuator gain	0.99
T_D derivative time constant	0.01 s
V_{RMAX} saturation max. limit	10.5 p.u.
V_{RMIN} saturation min. limit	0.0 p.u.
V_{RBASE}	15.90 V
T_A AVR actuator time constant	0.0001 s

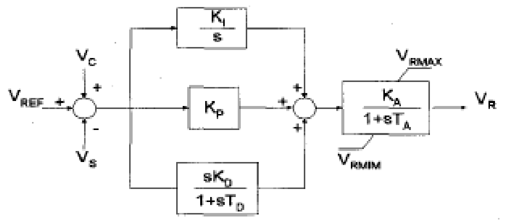

Fig. B-I. AVR transfer function typical representation

TABLE B-II
GENERATOR EXCITER

IEEE 421.5 AC brushless type model parameter	**Value**
K_E	1.00
T_E	0.229 s
S_E (E_{FD} = 8.8 p.u.) S_E (E_{FD} = 4.6 p.u.)	0.02 0.02
E_{FDMIN} E_{FDMAX}	0 p.u. 15.31 p.u.
E_{FDBASE}	23.25 V
I_{FDBASE}	253.08 A

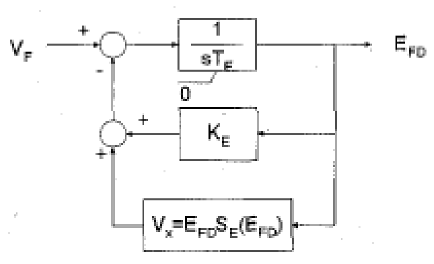

Fig. B-II. Exciter transfer function typical representation (simplified version of IEEE Std. 421.5 AC8B excitation system model)

C. Modeling of Speed Governor of Gas Turbine

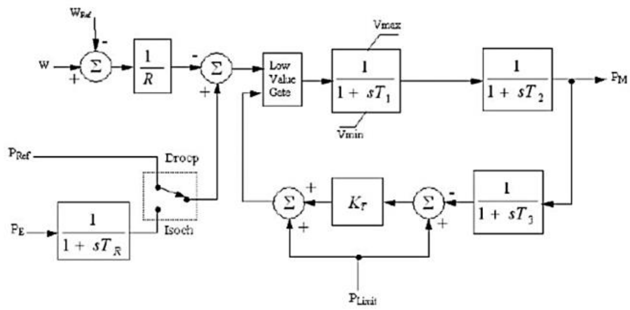

Fig. C-I. ETAP software gas-turbine governor model (GT2 model)

TABLE C-I
GAS TURBINE GENERATOR PARAMETERS OF GOVERNOR

Parameter	**Value**
P_{REF} Load Reference	1 per unit
P_{LIMIT} Ambient Temperature Load Limit	0.81 per unit
V_{MAX} Maximum Fuel Valve opening	1.1 per unit
V_{MIN} Minimum Fuel Valve opening	- 0.07 per unit
BASE Governor base power	12.74 MW
R Load / Speed Droop	0.035 per unit (droop) 0.1 per unit (isochronous)
T_R Load Sensing Time constant	0.005 s
T_1 Governor Time constant	0.1 s
T_2 Combustion Chamber Time constant	0.3 s
T_3 Turbine Thermal Time constant	0.5 s
K_T Load limit thermal sensitivity gain	2 per unit

D. Default relay settings of the Interface Protection Device (SPI)

TABLE D-I
DEFAULT SETTINGS FOR SPI DEVICE (STANDARD CEI 0-16)

Protection Function	**Tripping Threshold**	**Tripping Delay Time**	**Fault Clearing Time**
Ordinary Over/Under-Voltage Functions			
Overvoltage 59.S1	1.10 Un	3 s	3.07 s
Overvoltage 59.S2	1.20 Un	0.60 s	0.67 s
Undervoltage 27.S1	0.85 Un	1.5 s	1.57 s
Undervoltage 27.S2	0.4 Un / 0.3 Un	0.20 s	0.27 s
Restrictive & Permissive Over/Under Frequency Functions			
Overfrequency 81>.S1 restrictive threshold	50.2 Hz	0.15 s	0.22 s
Underfrequency 81<.S1 restrictive threshold	49.8 Hz	0.15 s	0.22 s
Overfrequency 81>.S2 permissive threshold	51.5 Hz	1 s	1.07 s
Underfrequency 81<.S2 permissive threshold	47.5 Hz	4 s	4.07 s
Voltage Restraint Functions			
Zero sequence overvoltage 59Vo	5% ref. to √3 Un or 3 En	25 s	25.07 s
Negative sequence overvoltage 59Vi	15% ref. to Un or En		
Positive sequence undervotage 27Vd	70% ref. to Un or En		

VII. VITA

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Mr. Paolo Marini received his Master of Electrical Engineering degree in 2005. In 2006 he joined the Department of Electrical Engineering of Tecnimont Company based in Milan, Italy. He is an Individual Member of the International Council on Large Electric Systems (CIGRE), an Individual Member of IEEE Industry Applications Society (IAS), and an Industrial Member of the Italian Electrotechnical Committee (CEI), Technical Committee CT2 “Rotating Machines”.
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