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Development of Engine Control Unit for Gas Turbine Starter of Fighter Aircraft

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Abstract: ***The progress in the gas turbine field and advanced measuring techniques have been dramatically accelerated with the advent of modern control during the last two decades. In this scenario, this project is aimed at study and design of an Engine Control Unit (ECU) for a Turbo Shaft Gas Turbine Starter. The starter is used to start the main engine of a fighter aircraft. The ECU is a dual lane controller which controls the fuel flow to the Gas Turbine Starter engine to maintain its speed, temperatures and pressures in safe limits for proper starting of the main aero engine. It is a Microcontroller based Digital Electronic Control. It changes a 3-phase stepper motor position either in forward (clockwise) or backward (anticlockwise) direction which in turn modulates the fuel to the combustion chamber of the starter engine to maintain its structural parameters (rotor speed) and thermodynamic parameters (pressures and temperatures) within the specified limits for safe operation.***

Keywords: Engine Control Unit, Gas Turbine Starter, Fighter Aircraft, Stepper Motor

1. Introduction

There are several ways of starting the main engine of a fighter aircraft. One of the method is starting through another small gas turbine engine (Gas Turbine Starter) or simple starter.

The starter engine is also a Gas turbine engine whose structural parameters such as speed and thermodynamic parameters such as Temperature and pressure are to be contained within a specified limit to avoid any catastrophic failure. This is accomplished by properly controlling the admission of fuel into the starter engine.

Engine Control Unit (ECU) is an Avionics unit which plays an important role in control of fuel flow to the Starter Unit, which starts the main engine. It provides full authority control of fuel flow to the Starter Unit. The ECU takes input from various engine mounted sensors and takes appropriate decision to control the fuel flow into the starter engine. Apart from Engine Control, the ECU also needs to handshake with appropriate aircraft avionics Line Replaceable Units (LRU) for indication to the outside World and also to the pilot. Engine Control Unit has to ensure Smooth light up scheduling, Surge free acceleration, Governing at maximum speed until output shaft speed reaches self-sustaining speed, Shut off the engine after reaching cut-off speed, or timeout, or over temperature and speed runaway conditions.

ECU is a microcontroller based Digital PID controller to start the Starter Unit, accelerate and control the Starter Unit by controlling the fuel flow with the help of stepper motor which in turn starts the Main Engine. It has two identical PCBs, Main Processor card (Lane 1) and the Emergency Processor card (Lane 2). During the normal functionality, the main processor will be controlling the stepper motor and the outputs. The Emergency processor will be checking the health of the main processor. Once any failure in the main processor is detected, the Emergency processor takes the control of the stepper motor and the outputs.

2. Literature Survey

B. S. Bhangu and Kaushik Rajashekara, in their paper, “Control strategy for electric starter generators embedded in gas turbine engine for aerospace applications”, explain that due to space constraints a practical solution for UAVs is to employ electricstarter generators (ESG) embedded in gas turbine engines to facilitate electric engine crank, aid the engine to the desired idle speed and generate power to drive the onboard auxiliaries. However, the traditional sensors that provide accurate knowledge of the machine rotor position to ease precise control of the ESG cannot be used because of the adverse operating conditions. The entire hardware and control architecture was tested on an experimental test rig using a dynamometer to mimic the gas turbine engine. Following the testing, the system was commissioned into the gas turbine Small Electric Engine Demonstrator (SEED).

Song Ma, Jianguo Tan, Yongqian Ning and Zichang Gao, presented a paper on “Modeling and simulation of gas turbine starter and fuel control system”, which explains that Gas turbine starter is an important component of aero-engine gas turbine starting system, and its performance directly affects the starting ability of an aero-engine. In order to meet the necessities of starter power for different types of large engines and provide theoretical foundation for modification of starters, the paper focuses on the performance of gas turbine starter and its fuel control system. The design and operating principle of the system were firstly analysed. Based on the AMESim mechanical hydraulic simulation software, the component-level model of fuel control system was built. Then the model of the starter portion was established according to the fundamental principles of gas dynamics and thermodynamics. By comparing the simulation results of the model with the experimental data, results showed that the established model met the requirements of engineering and thus, provided a simulation platform for future research of gas turbine starter.

Weili Dai, TongcaiXiu, Huizhen Wang and Yangguang Yan, explain in their paper, "Control of a novel dual stator doubly salient aircraft engine starter-generator", that a novel dual stator doubly salient Aircraft Engine Starter-Generator System has been designed and constructed for an aircraft engine application. The system is based on a dual-stator doubly salient Electromagnetic machine, which was chosen for its simplicity, ruggedness, high speed capability, low torque ripple in motoring and low output voltage ripple in generating. The paper describes the motor control system algorithms and hardware which were used to control the motor over its operating speed range from standstill to 11425rpm in both motoring and generating modes. There are novel features in this starter-generator control system, the particular motor structure, angle advanced control strategy which were adopted in aircraft engine starting process, which controlled the value of advanced angle to maintain optimum torque at medium and high speed automatically. The transition between starting and generating process was satisfied by a hardware-based digital commutation controller which generated phase firing pulses for the inverter based on the machine rotor angle, pulse width, and pulse advance. The results of aircraft engine cold start show that the brushless starter-generator system had good starting character and smooth starting torque.

R. Bojoi, A. Cavagnino, A. Tenconi and S. Vaschetto, "Control of Shaft-Line-Embedded Multiphase Starter/Generator for Aero-Engine", discuss thattheir paper deals with a shaft-line-embedded multiphase electrical machine to be connected to the high-pressure shaft of an open-rotor jet engine. An asymmetrical six-phase induction machine (IM) was proposed for this application. The main focus of the paper was on the control of the six-phase IM, to verify its overload capabilities and postfault operations. The realized control used a direct-flux vector control scheme-based on a double-stator approach, where each 3-phase winding set was independently controlled. This way, the fault-tolerant behaviour of the drive system was enhanced. The torque and speed control loops were implemented in a dedicated multiple three-phase drive, and a scaled prototype (10 kW, 6000 r/min) had been tested. The overload capability was verified both in generation and motoring mode, for different speeds and torque up to 150% of the rated one. Lastly, the transitions between healthy and faulty modes are reported for open phases and encoder faults. The obtained results validate the feasibility of the proposed drive solutions.

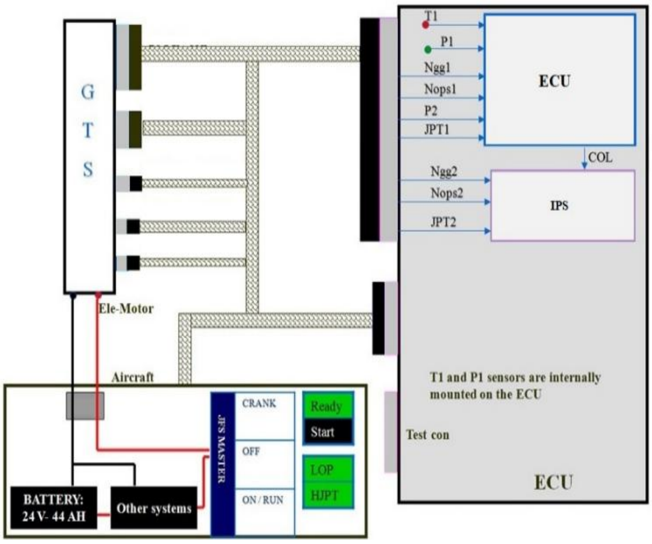
V. B. Hart, "Multijet airplane starter-generator controls", explains that most electric control systems and their respective components designed for a multijet airplane are in many respects much the same as those used on reciprocating engine-type airplanes. It is true also with respect to the starter and generator system as used on a previously developed 6-engine jet airplane. The main difference are the starter and generator components themselves. On a standard reciprocating engine-type airplane the two components are separate entities having their own control systems. On the multijet airplane, the starting and generating functions are performed by a single unit. The unit is called a "starter-generator" and is rated at 400 amperes, 30 volts direct current, capable of supplying a continuous output of 400 amperes at engine speeds from 4,000–8,000 rpm. The electric system designed to control the starter-generator and its supporting components were patterned, in the early designs, after comparable systems used on standard reciprocating-type airplanes. Modifications, and in some respects complete redesign, of parts of the control system were essential in order to provide a system which would perform according to the more exacting requirements demanded of it.

S.R. MacMinn and J.W. Sember, in their paper, "Control of a switched-reluctance aircraft engine starter-generator over a very wide speed range", explain that an electric direct-drive gearless starter-generator had been designed and built for an aircraft-engine application. The system was based on switched reluctance motor, which was chosen for its simplicity, ruggedness, high-speed capability, and efficiency. The motor control system algorithms and hardware were used to control the motor over its operating speed range from standstill to 48000 RPM in both monitoring and generating modes. The unique features of the starter-generator control system are a closed-loop regulator which controls the amount of firing angle advance to sustain optimum at high speed, and a hardware based digital commutation controller which generates phase firing pulses for the inverter, pulse width, and pulse advance.

3. Hardware Implementation

Engine Control Unit

ECU is microcontroller-based unit which computes the control function to regulate the fuel flow and to provide proper dynamic characteristics and steady state speed holding characteristics. The ECU and GTS interface is as shown below:



The system in conjunction with the aircraft electrical system, starts, detects light up and accelerates the GTS as per the internally generated sequence. The gain in the control law is designed that the demand is followed without exceeding the limiting/surge conditions.

The ECU has main processor (main or Lane 1) and a standby processor (Lane 2) or Independent Protection System (IPS). A Change Over Logic (COL) monitors the health of main processor and transfers the control to IPS backup lane in case of main processor failure. The main controller provides the full authority control of fuel flow, while the IPS monitors for runaway conditions in normal mode.

In providing fuel flow control, ECU ensures:
- Smooth light up scheduling
- Surge free acceleration
- Governing at maximum speed, until output shaft speed reaches self-sustaining speed.
- Shut off the engine after reaching cut-off speed, or timeout, or over temperature and speed runaway conditions.

The Main and the IPS exchange their health condition. When main controller failure is detected at any time after start, IPS can take over at that instant without affecting the engine run. In case the Main failure is detected before start on Ground, the GTS start is aborted. However, for inflight start the GTS start is enabled even though one of the Lane has failed.

The ECU comprises of 4 cards, namely:
1) Power Supply Card
2) Main Controller Card
3) Independent Protection Card
4) Input Output Card

Power Supply Card

The power supply card provides the 5V, +15V, –15V and +24V taking from the aircraft 28V supply. This system caters for full operation from 12V to 31.5V DC. This is ensured by the use of an MDM module. The power supply card also houses driver transistors for driving the stepper motors.

Main Controller Card

This card is built around 87C51 Microcontroller. The microcontroller is provided with real-time emulation and embedded trace support, together with 256KB of embedded high speed flash memory. All computation and control functions are executed through this card. The main function of this card is to provide the full control of fuel flow by implementation of control law. It acquires inputs from I/O card, it drives the stepper motor and also it indicates the status by driving relays.

Independent Protection System

IPS is a full-fledged independent protection system, acquires NGG2, NOPS2 and JPT2 signal and checks for over speed and over temperature and implementation of shutoff states. Under run away conditions, it closes FSOV and shutoff engine when the main controller is healthy. At any time, main controller failure is detected, IPS performs open loop control to accelerate the engine to the maximum speed apart from monitoring. It consists of another 87C51 Micro controller.

Input Output Card

All the engine mounted sensors are interfaced with the ECU through the Input Output card. This card contains the necessary signal conditioner and the ADC to process the sensor signal, amplify it and convert it into a digital form for the processor card to access. I/O card has all the signal conditioning, data acquisition and processing circuits encompassed in it. This has relays to drive the signals.

Mother Board and Col

The Mother Board provides the interconnections among the Main controller card, IPS card and the power supply module connector. The interconnections from the external connection are routed as an integral part of the mother board.

The external connections are routed to the mother board through a connector. The 28V power is supplied and the ECU has an RS422 output through which we can download the data of the engine run.

RS422 Output

Apart from the engine control action, the ECU stores the engine parameters in the EEPROM. These data can be extracted through the RS422 bus. The ECU has Test Connector through which the data can be extracted. The Parameters output are P1 and T1 up to start Light up and afterwards NGG, NOPS, JPT, P2 and SMPOS. A short between 2 pins of the test connector will enable the data extraction.

At power ON, ECU checks for the short pins on the Test Connector. If short is present (TEST mode ON), then it enters into RS422 Data dumping mode and abort the engine start function.

At power ON, if ECU does not detect short on the pins, then it enters in to engine control mode.

Software Implementation

ECU Software

The Control Program is written in Assembly language to drive the PPI, WDT, MUX, ADC etc. The frequency calculation etc., are also written in 87C51 assembly code. The main control law and other look up tables are written in C language. The final code is Cross compiled and linked through AD2500 Compiler. A final HEX code is generated. The HEX file is dumped into the Non-Volatile Memory of the ECU processor.

4. Software Loading and Implementation

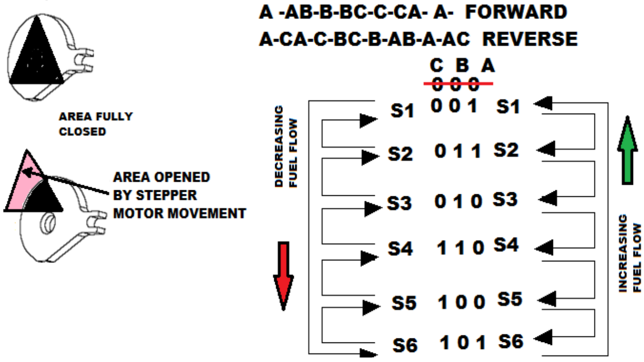
The software linking, compiling and loading are given in thefollowing steps:
a) All the individual Programs are linked as single project using AD2500 Linkerand compiled in to a hex file.
b) The output of the Cross compiler is stored.
c) The Check sum is noted. (the number of 1s in the program).
d) The 87C51 in which the program to be loaded is kept in the UV eraser in such a way that the programming window is facing the bottom from where the UV ray emerges.
e) The UV eraser is made ON and a time of 3 minutes is allowed for the data to get erased.

f) Then the 87C51 IC is kept on the programmerhardware and locked.
g) The programming hardware is connected to Programming PC.
h) The programming software selects INTEL 87C51 etc.,
i) The 87C51 IC is checked for Blank data (all 00)
j) If the IC is not fully Blanked, once again the IC is removed from the programming hardware and needs to be kept in UV eraser.
k) Once the Blank data on the 87C51 is ascertained, the output file is loaded in to the microcontroller chip.
l) While loading Program, LOAD and VERIFY mode is selected.
m) Hence after writing the HEX code, the Programmer verifies the CHECK SUM.
n) If the check sum of loaded program and the check sum of 87C51 IC after program loading tallies, the then Programmer displays VERIFIED SUCCESSFULLY.
o) Now the IC is ready for fixing in the Hardware.
p) The IC is inserted into the Pin slot of Processor board and secured tightly.
q) Also, the Programming window is Masked with Dark Tape.

5. Operation Principle

The ECU can do two functions. Either it will send the data pertaining to the previous engine state operation (Test Mode) or Engine Start and Control mode. This is decided by the signal state of the Test mode pins of the test connector.
At power ON, ECU checks for the short pins on the Test Connector. If short is present (TEST mode ON), then it enters into RS422 Data dumping mode and abort the engine start function. It outputs the previous engine run data for last 4 starts through the RS422 lines to the user PC.

At power ON, if ECU does not detect short on pins, then it enters in to engine control mode. The operation of the ECU in engine control mode is as follows:



At power ON, the stepper motor is moved backwards by 250 steps (at rate of 200 steps/sec) so that it comes to a mechanical end stop. For this the ECU produces the Stepper motor bit pattern A-CA-C-BC-B-AB……A-CA in reverse direction. The phase change between A to CA and CA to C and so is maintained for 10milli seconds. This makes the stepper motor shaft to rotate in anti-clockwise direction and closes the cam plate fully. The metering valve position i.e. Stepper Motor Position (SMPOS) is now taken as zero counts. This operation is called as POWER ON RESET.Power On Reset of Stepper Motor is as shown below:

On receiving the Start Command, the stepper motor is moved to 50 steps forward.

The ECU enables the discrete output (28V DC) STARTER MOTOR/IGN ON command to latch a Relay in the aircraft to latch 24V 400A supply to start the starter motor of the GTS.

This results in GTS rotation and the Ignition to GTS ON.

ECU starts measuring the inputs NGG, NOPS, P2, JPT, P1 & T1, provides another discrete output command (28V DC) FSOV ON when the NGG speed > 2000 RPM.

This makes the air sucked by the GTS is mixed with the fuel and gets ignited. Hence the RPM increases. The JPT also increases.

It moves the stepper motor to increase the NGG RPM.

The ECU measures and calculates the NGG RPM and JPT to check itsrequired conditions.

If the condition is achieved, it confirms as Light up detected. It provides another 28V DC discrete output to the Aircraft event recorder as GTS Light up detected.

If light up logic is not satisfied within 12 seconds, the ECU aborts the GTS operation issuing another Discrete Output Command (28V DC) to a relay ABNORMAL SHUT OFF which cuts off the +28V supply to FSOV, Starter Motor and Ignition Relay. This discrete output is also sent to Cockpit so that ABNORMAL SHUT OFF lamp lits in the cockpit.

This makes the GTS to shut down (The GTS operation aborted as a Safety measure).

If the Light up is successful, the ECU computes the Control law based on the acceleration rate of the engine, FSOV ON command is still ON and it admits fuel into combustion chamber and gas generator acceleration takes place.It moves the stepper motor forward to increase the gas generator speed NGG to Maximum RPM.

During the acceleration of the Gas generator speed to Maximum RPM, The ECU removes the STARTER MOTOR /IGN ON Command when the NGG speed Crosses 50% of Max NGG.

This results in Starter Motor getting electrically disengaged. The starter motor will be mechanically running to provide the NGG signal through the Magnetic pick up mounted on it.

6. Conclusion

This project is about design and development of an Engine Control Unit to control the Gas Turbine Starter Engine by regulating the fuel flow. The focus of this project was on the study and establishment of GTS operation requirements, the interface requirement of ECU with GTS and its associated sensors. Based on the requirements, a Dual Lane Control with embedded architecture has been developed as Engine Control Unit.

The ECU developed is a microcontroller based Digital PID controller to start the Starter Unit, accelerate and control the Starter Unit by controlling the fuel flow with the help of stepper motor which in turn starts the Main Engine. The design was using 87C51 micro controller which is cost effective, most reliable and best suited for ECU of starter engine type application.

During testing of the ECU for its control action, the accurate measurement of the Gas Turbine Starter behavior and swift action by the ECU were the highlights - The key success of this project.

Thus, the objective of the project has been achieved by design, development and testing of the **Engine Control Unit**.

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