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MINISTERO DELLO SVILUPPO ECONOMICO

Ricerca di Sistema elettrico

Sviluppo e sperimentazione dell'assetto multi-fuel in una micro-turbina a gas Turbec T100

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A. Bo, S. Attanasi, S. Cassani, A. Assettati

Report RdS/PAR2015/184

SVILUPPO E SPERIMENTAZIONE DELL’ASSETTO MULTI-FUEL IN UNA MICRO-TURBINA A GAS TURBEC T100

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Le attività descritte in questo rapporto sono state largamente influenzate dallo spessore professionale di Leandro Pagliari, oramai giunto alla soglia del pensionamento. L’ENEA perderà inevitabilmente una professionalità di assoluto rilievo, i colleghi molto di più.

Indice

Sommario

L'implementazione dell'assetto *multi-fuel* sulla µGT Turbec T100 in dotazione all'ENEA ha richiesto la duplicazione del sistema di alimentazione, con sostanziali modifiche apportate sia all'hardware sia al software di controllo della turbina a gas. Il combustore sperimentale ARI 100 T2 è provvisto di ugelli dedicati per l'alimentazione a gas naturale e a syngas la cui gestione non è prevista nella versione standard della Turbec T100. E' stato pertanto realizzato e installato un sistema di condizionamento esterno (ECS) innestato tra il PLC originale della µGT e il sistema di alimentazione del combustibile. Si è deciso di implementare l'ECS sfruttando il PLC e il software di sviluppo integrati nel DCS (Distributed Control System) dell'impianto ZECOMIX, aggiungendo un nuovo nodo dedicato alla µGT. La transizione tra i due sistemi di alimentazione del combustibile è avvenuta in condizioni di completa stabilità di esercizio della macchina, come evidenziato dall'andamento costante della TOT (Turbine Outlet Temperature), della velocità di rotazione (n_{MGT}) e della potenza elettrica P_{el} prodotta dalla µGT durante l'esecuzione dei test effettuati per validare sperimentalmente la strategia di controllo. Le attività fin qui svolte confermano pienamente quanto previsto nell'annualità precedente [1] ed aprono la strada per il consolidamento della strategia di controllo implementata, con l'obiettivo di testare la sequenza di transizione dall'alimentazione a gas naturale della µGT verso miscele combustibili idrogenate con contenuto variabile di idrogeno.

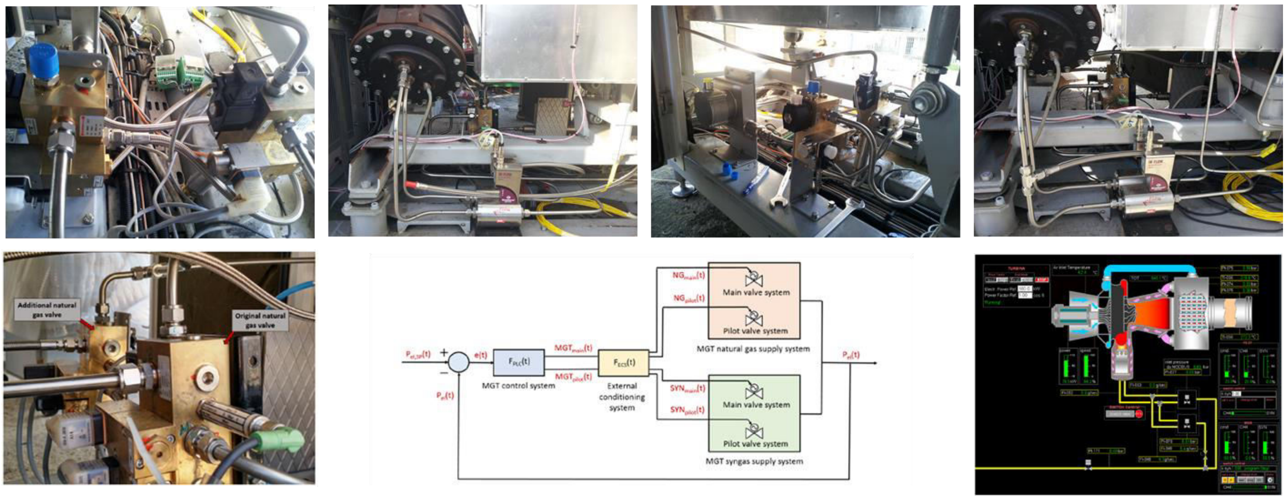

Figura 1. Sintesi grafica delle modifiche hardware e software al sistema di controllo realizzate dall'ENEA sulla µGT Turbec T100 in dotazione.

1 Introduzione

La micro-turbina a gas (µGT) Turbec T100 nella sua versione commerciale è equipaggiata con un sistema di alimentazione del combustibile composto da una linea di iniezione *main* che inietta il combustibile nella sezione premiscelata del combustore e da una linea *pilot* che inietta il combustibile nella sezione diffusiva. L'alimentazione del combustibile è gestita mediante il sistema di controllo, i cui componenti hardware fondamentali consistono in un PLC (Programmable Logic Controller) e due valvole di regolazione asservite rispettivamente alla linea *main* e alla linea *pilot*.

Il PLC gestisce l'apertura delle valvole di regolazione mediante delle sequenze di controllo in retroazione attuate con l'emissione di due segnali di controllo in corrente modulati nell'intervallo 0 – 20 mA. Le valvole di controllo sono assemblate in un blocco compatto che alloggia le due valvole a solenoide controllate mediante segnale PWM (Pulse Width Modulation) e un orifizio contiguo con la linea *pilot* che assicura la continuità di alimentazione del combustibile. Il segnale PWM ha la forma di un'onda quadra il cui massimo valore è pari a 1 quando la valvola a solenoide è completamente aperta e, alternativamente, pari a 0 quando la valvola a solenoide è chiusa. Le valvole a solenoide hanno quindi due stati, aperto/chiuso, mentre il controllo si ottiene modulando il tempo di permanenza di uno stato rispetto all'altro all'interno del periodo di riferimento dell'onda quadra. Il rapporto tra il tempo di apertura della valvola e il periodo dell'onda quadra si definisce ciclo di lavoro (*duty cycle*). Trascurando l'inerzia delle valvole, ovvero il tempo necessario per l'apertura e la chiusura, il *duty cycle* è direttamente proporzionale alla portata massica del combustibile iniettato in camera di combustione[1].

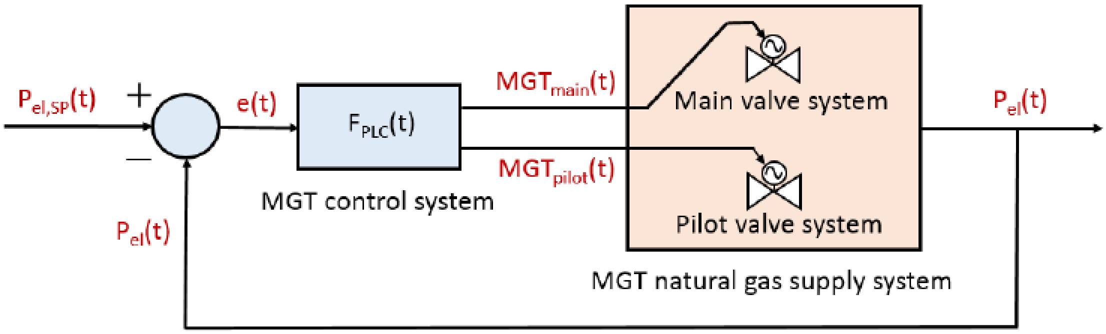

Figura 2. Schema di principio della logica di controllo dell'alimentazione del combustibile della µGT Turbec T100 [2].

La figura 1 illustra schematicamente la logica di controllo originale implementata sulla µGT Turbec T100. Tra i principali segnali in ingresso al PLC della µGT sono la potenza elettrica istantanea generata dalla macchina $P_{el}(t)$ e il set point $P_{el,SP}(t)$. Il sistema di controllo compara istante per istante i due segnali appena citati e, sulla base dell'errore definito come:

$$e(t) = P_{el,SP}(t) - P_{el}(t)$$

genera a sua volta la coppia di segnali MGT_{main} e MGT_{min} che movimentano le valvole di alimentazione del combustibile, rispettivamente delle linee *main* e *pilot*.[2] Il sistema di controllo della µGT è progettato per garantire l'erogazione della potenza elettrica desiderata a fronte dei molteplici disturbi provenienti dall'ambiente esterno al dominio di controllo. Nello specifico, se la funzione di errore *e(t)* è istantaneamente positiva (negativa) si verifica un difetto (eccesso) nella potenza elettrica erogata dalla µGT all'istante *t* rispetto al valore di set point, al quale il sistema di controllo reagisce aumentando (riducendo) il duty cycle di una o entrambe le valvole di controllo del combustibile o, in altri termini, aumentando

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[1] Per maggiori dettagli si rimanda all' Appendice, pagine 153-155.

[2] Per maggiori dettagli si rimanda all' Appendice, pagine 156-157.

(riducendo) la portata di combustibile avviata al combustore. Il sistema di controllo agisce quindi in maniera tale da garantire il funzionamento stabile della macchina minimizzando l'errore *e(t)*. I test condotti sulla μGT nella precedente annualità, hanno evidenziato la tendenza del sistema di controllo ad intervenire principalmente agendo sulla valvola *main* nell'intervallo di potenza elettrica compreso tra il 50% e il 100% del carico nominale. Di conseguenza, nell'intervallo di potenza appena citato, la valvola *pilot* è sostanzialmente insensibile alle variazioni di carico, se non in caso di transitori con notevoli variazioni di carico (e.g. dal 100% al 20%), durante i quali la valvola *pilot* viene movimentata per garantire la stabilità di combustione mediante la sezione diffusiva del combustore. Nell'intervallo di potenza inferiore al 50% del carico nominale, anche in assenza di bruschi transitori, si evidenzia un utilizzo attivo sia della valvola *main* che della valvola *pilot.* Quanto appena descritto rappresenta solo una descrizione parziale sia della logica di controllo sia dei parametri che in essa intervengono. Tuttavia, seppur semplificata, la descrizione si ritiene utile a comprendere la ratio delle modifiche al sistema di controllo descritte nelle righe seguenti[3].

2 Implementazione dell'assetto multi-fuel sulla μGT Turbec T100

L'implementazione del doppio sistema di alimentazione sulla μGT ha richiesto sostanziali interventi sia all'hardware sia al software della turbina a gas. Il combustore sperimentale ARI 100 T2 è provvisto di ugelli dedicati per l'alimentazione a gas naturale e a syngas la cui gestione non è prevista nella versione standard della Turbec T100. Una modifica diretta del codice implementato nel PLC della macchina richiederebbe un intervento da parte di personale specializzato Ansaldo-Turbec che, a fronte di costi senz'altro non trascurabili, implicherebbe comunque un limitato accesso alla *knowledge* del processo di implementazione, a causa alla evidente necessità di proteggere la proprietà intellettuale coinvolta nel processo oggetto di studio. Escludendo pertanto questa opzione, si è deciso di procedere in autonomia, intraprendendo un sentiero più rischioso che consentisse però il completo controllo del processo di implementazione e delle successive inevitabili variazioni, senza violare la proprietà industriale del costruttore. Nello specifico, è stato realizzato e installato un sistema di condizionamento esterno (ECS) innestato tra il PLC originale della μGT e il sistema di alimentazione del combustibile. Come primo tentativo si è deciso di implementare l'ECS sfruttando il PLC e il software di sviluppo integrati nel DCS (Distributed Control System) dell'impianto ZECOMIX, aggiungendo un nuovo nodo dedicato alla μGT. Dal punto di vista dell'operatore l'ECS rappresenta l'effettiva piattaforma di controllo della μGT dotata di interfaccia dedicata, mentre, dal punto di vista del sistema di controllo originale della T100, l'ECS rappresenta un "disturbo esterno" da compensare con la logica di controllo implementata nel PLC della macchina. L'idea è quindi quella di ingannare il sistema di controllo originale, che continua ad operare come se fosse presente solo un sistema di alimentazione e di utilizzare l'ECS per condizionare i segnali di controllo in uscita al PLC della μGT per la gestione di entrambi i sistemi di alimentazione. La logica del sistema di controllo originale schematizzata in figura 2, viene quindi modificata secondo lo schema di figura 3. Il sistema di controllo così modificato consente di gestire la transizione da un sistema di alimentazione all'altro (e viceversa) in una finestra temporale definita mantenendo la macchina in condizioni di esercizio stabile. Una volta terminata la sequenza di transizione, operazione che ammette anche l'utilizzo simultaneo di entrambi i sistemi di alimentazione, l'esercizio della μGT può proseguire secondo il protocollo standard. La sequenza di transizione è basata sui seguenti tre *step*:

1. start-up della μGT a gas naturale e raggiungimento della potenza di riferimento per l'esecuzione della transizione;
2. a potenza elettrica costante, transizione (totale o parziale) dall'alimentazione a gas naturale all'alimentazione a syngas mediante graduale chiusura della valvola *main* del gas naturale e corrispondente graduale apertura della valvola *main* del syngas;

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[3] Per maggiori dettagli si rimanda all' Appendice, pagina 157.

3. completa (parziale) chiusura della valvola *main* del gas naturale e sostentamento stabile della µGT con l'alimentazione a syngas (o ibrida gas naturale/syngas) e ripresa dell'esercizio della macchina secondo il protocollo standard.[4]

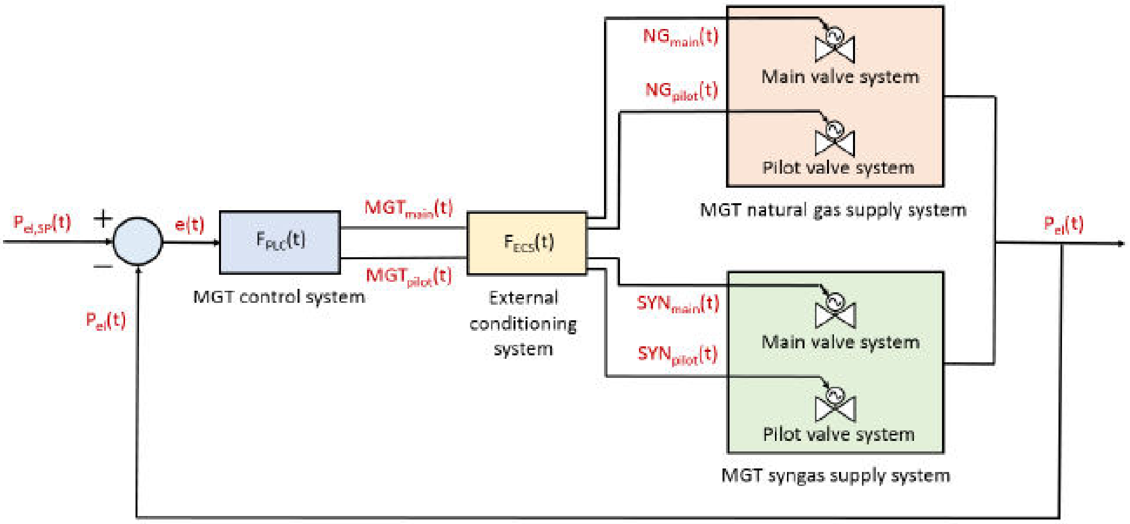

Figura 3. Schema di principio della logica di controllo implementata dall'ENEA per la gestione del doppio sistema di alimentazione del combustibile della µGT Turbec T100 [2].

Come illustrato in figura 3, l'ECS intercetta la coppia di segnali MGT_{main} *(t)* e MGT_{pilot} *(t)* in uscita dal PLC della µGT, condizionandoli con una sequenza di operazioni riassumibili in:

1. copia della coppia di segnali MGT_{main} *(t)* e MGT_{pilot} *(t);*
2. duplicazione della coppia di segnali copiati in due coppie distinte. La prima coppia di segnali sarà inviata al sistema di alimentazione a gas naturale, la seconda coppia al sistema di alimentazione a syngas. In seno a ciascuna coppia, un segnale è associato alla valvola *main*, mentre l'altro è associato alla valvola *pilot.* Ciascuno dei segnali mantiene l'intervallo di lavoro di provenienza pari a 0-20 mA.
3. Graduale attenuazione della coppia di segnali relativi al sistema di alimentazione a gas naturale.
4. Graduale incremento della coppia di segnali relativi al sistema di alimentazione a syngas.
5. Invio delle due coppie di segnali condizionati ai rispettivi sistemi di alimentazione del combustibile.[5]

La sequenza elencata nei punti da 1 a 5 prosegue fino al completamento della transizione da un sistema di alimentazione all'altro che, come già detto, può completarsi con la completa sostituzione del sistema di alimentazione a gas naturale con il suo omologo a syngas o con un assetto ibrido che prevede l'utilizzo di entrambi i sistemi di alimentazione. I test sperimentali condotti sulla µGT equipaggiata con doppio sistema di alimentazione costituito dalla duplicazione dell'hardware commerciale, hanno evidenziato che un tempo di transizione pari a 300 s consente il passaggio da un sistema di alimentazione all'altro senza l'insorgere di instabilità operative, a patto di effettuare il condizionamento dei segnali provenienti dal PLC della macchina con tempi di elaborazione non superiori a 5 ms. Conseguentemente la frequenza di elaborazione dell'ECS per l'esecuzione della sequenza precedentemente elencata nei punti da 1 a 5 deve essere non inferiore a 200 Hz.[6] La figura 4 a sinistra illustra l'installazione a bordo macchina di un singolo blocco valvole per l'alimentazione a gas naturale, mentre nella stessa figura a destra si può osservare la configurazione finale del doppio sistema di alimentazione costituito da due blocchi valvole identici. La figura 5 illustra un particolare dell'interfaccia grafica realizzata per l'esercizio della µGT in assetto *multi-fuel*.

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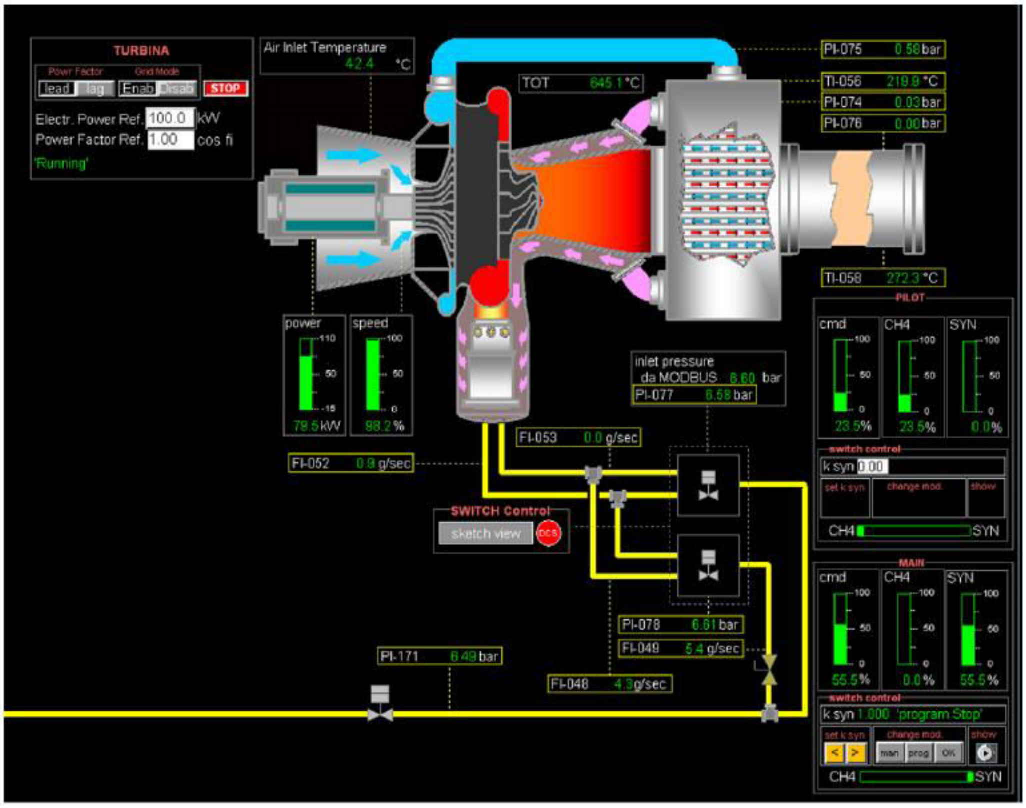
[4] Per maggiori dettagli si rimanda all'Appendice, pagina 160.

[5] Per maggiori dettagli si rimanda all'Appendice, pagine 161-162.

[6] Per maggiori dettagli si rimanda all'Appendice, pagine 163-167.

Figura 4. Dettaglio delle connessioni fluidodinamiche del blocco valvole nella versione standard del sistema di alimentazione del combustibile (sinistra). Il doppio sistema di alimentazione installato dall'ENEA a bordo della Turbec T100 in dotazione.



Electr. Power Ref. 100.0 kW
Power Factor Ref. 1.00 cos fi
'Running'
Air Inlet Temperature 42.4 °C
TOT 645.1 °C
power 79.5 kW
speed 98.2 %
FI-052 0.9 g/sec
FI-053 0.0 g/sec
PI-075 0.58 bar
TI-056 219.9 °C
PI-074 0.03 bar
PI-076 0.00 bar
TI-058 272.3 °C
inlet pressure da MODBUS 6.60 bar
PI-077 6.58 bar
PI-078 6.61 bar
FI-049 5.4 g/sec
PI-171 6.49 bar
FI-048 4.3 g/sec

PILOT: cmd 23.5% CH4 23.5% SYN 0.0%
k syn 0.00

MAIN: cmd 55.5% CH4 0.0% SYN 55.5%
k syn 1.000 'program Stop'

Figura 5. Interfaccia grafica dell'ECS (External Conditioning System) realizzata per l'esercizio *multi-fuel* della Turbec T100 modificata dall'ENEA.

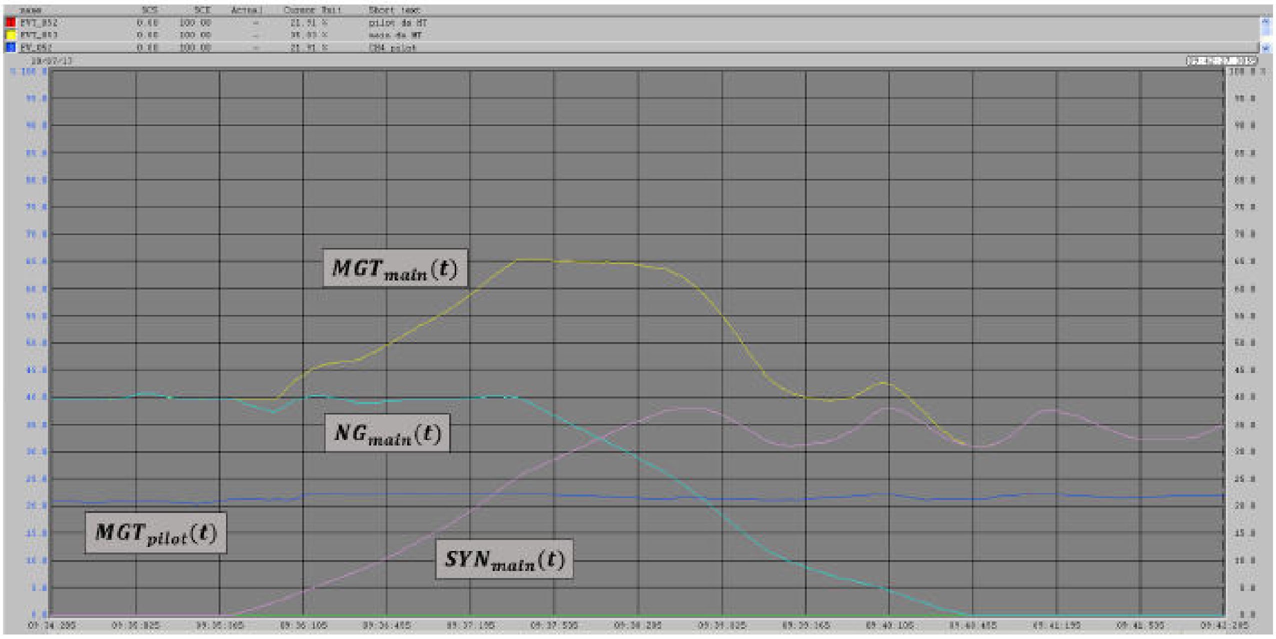


Figura 6. Andamento dei segnali di controllo delle valvole *main* del combustibile durante la transizione da un sistema di alimentazione all'altro. Il segnale di controllo della valvola *pilot* (azzurro) rimane costante durante tutta la transizione, il segnale della valvola *main* del gas naturale (celeste) progressivamente si attenua mentre il suo omologo a syngas (rosa) subisce un incremento. Il segnale di controllo della valvola *main* in uscita dal PLC (giallo) ha un andamento tale da compensare il disturbo causato dalla fase di transizione. I segnali sono monitorati acquisiti in tempo reale dal modulo ECS.

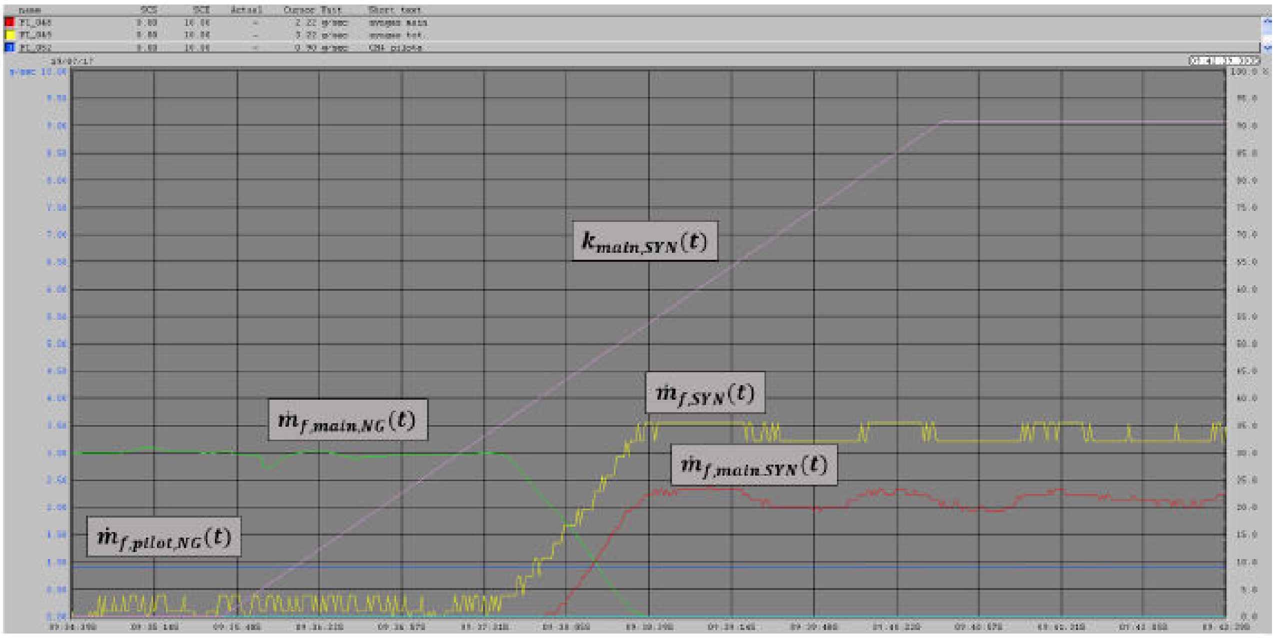


Figura 7. Andamento delle portate massiche di combustibile relative alle valvole *main* del gas naturale (verde) e del syngas (rosso), alla valvola *pilot* (azzurro) del gas naturale e alla portata complessiva del sistema di alimentazione del syngas (giallo) durante la fase di transizione. Il tracciato rispecchia l'andamento dei segnali descritto nella figura precedente. I segnali sono monitorati acquisiti in tempo reale dal modulo ECS.

Le figure 6, 7 e 8 illustrano l'evolversi delle grandezze più significative durante l'esecuzione di uno dei test eseguiti con successo per la validazione sperimentale della transizione da un sistema di alimentazione all'altro. Nello specifico, la figura 5 illustra la variazione dei segnali di controllo delle valvole di controllo *main* relative all'alimentazione a gas naturale (NG_{main}) e a syngas (SYN_{main}), confrontati con l'omologo segnale in uscita (MGT_{main}) dal PLC della µGT durante la sequenza di transizione del sistema di alimentazione. La figura 6 illustra la corrispondente variazione delle portate massiche alle valvole di controllo *main* del gas naturale e del syngas. La figura 7 infine dimostra che la transizione dal sistema di alimentazione a gas naturale al sistema di alimentazione a syngas è avvenuta in condizioni di completa stabilità di esercizio della macchina, come evidenziato dall'andamento costante della *TOT* (Turbine Outlet Temperature), della velocità di rotazione (n_{MGT}) e della potenza elettrica P_{el} prodotta dalla µGT durante la sequenza di transizione.

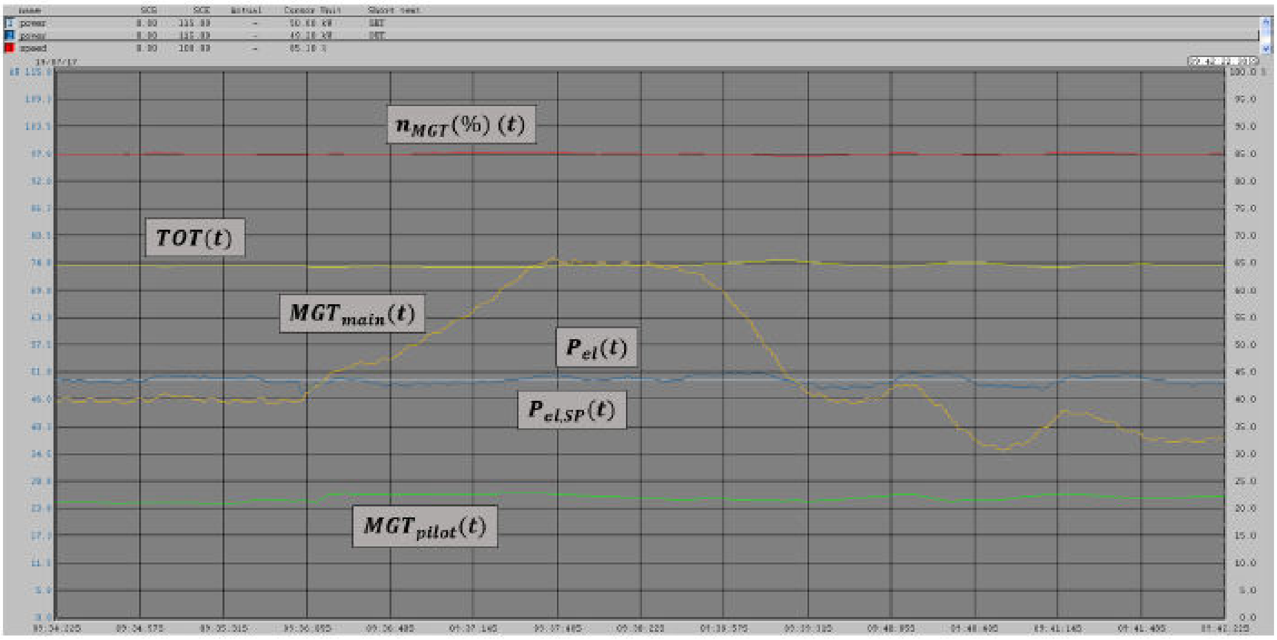


Figura 8. Andamento delle grandezze principali della Turbec T100 modificata dall'ENEA durante la fase di transizione da un sistema di alimentazione del combustibile all'altro. Si può osservare che la TOT (giallo), la velocità di rotazione (rosso), la potenza elettrica generata (azzurro) e il segnale di apertura della valvola *pilot* (verde) rimangono stabili durante tutta la fase di transizione. I segnali sono monitorati acquisiti in tempo reale dal modulo ECS.

3 Conclusioni

Nella precedente annualità, le conclusioni del rapporto sulle attività preliminari per l'implementazione dell'assetto multi-fuel della µGT Turbec T100 recitavano: *"… Le attività svolte sono da considerarsi preliminari ma fondamentali per la sperimentazione sull'utilizzo di miscele gassose ad alto contenuto di idrogeno e inerti quale combustibile per impianti turbogas. Tutti i test effettuati oltre a confermare la bontà delle scelte effettuate, prima fra tutte, la strategia di controllo per la transizione "a caldo" da gas naturale a syngas, consentono una visione più nitida degli obiettivi futuri. Tra questi, il prossimo passo consisterà nella duplicazione del sistema di alimentazione e nel test della strategia di transizione in condizioni sempre più prossime a quelle reali. Il primo di questa serie di test sarà realizzato eseguendo lo switch da "gas naturale a gas naturale", ovvero con due sistemi di alimentazione gemelli che consentiranno la validazione della procedura e la successiva automatizzazione mediante un algoritmo implementato in ambiente ABB Control Builder…"*.

Le attività fin qui svolte confermano pienamente quanto previsto ed aprono la strada per il consolidamento della strategia di controllo implementata, con l'obiettivo di testare la sequenza di transizione dall'alimentazione a gas naturale della µGT verso miscele combustibili idrogenate con contenuto variabile di idrogeno.

4 Riferimenti bibliografici

[1] G. Messina et al., "*Messa in marcia ed esercizio della sezione di potenza dell'impianto ZECOMIX*", Report RdS/PAR2015/228, AdP MiSE-ENEA, Ricerca di Sistema Elettrico, 2016.

[2] Alessandro Bo, "*Transition phase from natural gas to syngas in a dual fuel DLN MGT combustor*", Tesi di Laurea Magistrale in Ingegneria Meccanica, Università degli Studi Roma Tre – ENEA, relatori Prof. G. Cerri, Prof. G. Chiatti, Ing. E. Giacomazzi, Ing. A. Di Nardo, Ing. G. Messina, AA 2016-2017.

APPENDICE

Transition phase from natural gas to syngas in a dual fuel DLN MGT combustor

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AA 2016-2017

Chapter 9

Switch procedure from natural gas to syngas

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Chapter 9

Switch procedure from natural gas to syngas

One objective of the thesis has been the modelling of a control law capable to switch from the natural gas supply system to the syngas supply system in a Turbec T100 P MGT equipped with the dual fuel ARI 100 T2 combustor.

Excluding all parameters that need to be met in order to achieve stable combustion, the switch procedure is subjected to the following constraints:

- constant electrical power output P_{el}
- the Wobbe index WI of each fuel must be kept within the operational interval allowed by the corresponding supply system

9.1 Original control logic in Turbec T100 MGT

First of all an understanding of the original micro gas turbine (MGT) control system is necessary. As already shown in figure 7.8, the commercially available Turbec T100 P MGT is provided with one gaseous fuel supply system connected to a premixed (main) fuel line and to a diffusion (pilot) fuel line. Appropriate setting in its control panel allows to feed the MGT with either natural gas, which is the main fuel, or biogas.

The core component of the MGT control system is a programmable logic controller (PLC) which manages, through a feedback loop, the control signals that operate the fuel valves. The fuel supply system consists of a pilot valve and a main valve which respectively adduce fuel to the pilot and main fuel nozzles. These fuel injections take place in appropriate locations inside the combustor and are responsible for a diffusion and a premixed combustion regime respectively.

The valves are solenoid valves controlled through pulse width modulation (PWM) signals which are signals modulated in their temporal width. The signal resulting from such control is a square wave which attains the maximum value of 1 when the solenoid supply voltage completely opens the valve (state 1 or ON state) and attains the minimum value of 0 when the solenoid supply voltage is insufficient to open the valve i.e. when the valve is completely closed (state 0 or OFF state). Such square wave is characterized by a constant period T_{PWM} that, if repeated for a sufficiently long time, assumes the shape of a train of impulses as shown in figure 9.1.

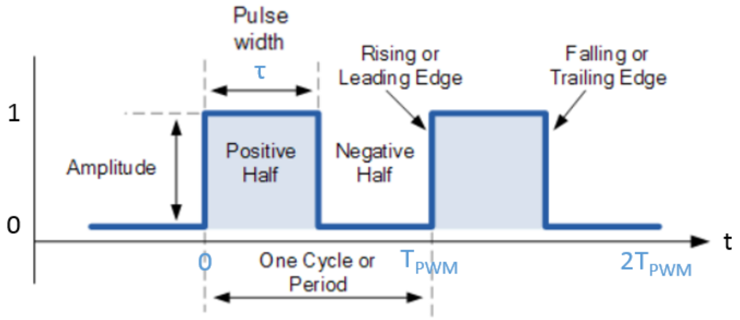


Figure 9.1: ***Train of impulses generated with PWM control technology***

Within the period T_{PWM} is possible to identify an *active* time τ in which the PWM signal corresponds to state 1 and a *passive* time $(\tau - T_{PWM})$ in which the PWM signal corresponds to state 0. The ratio between the active time τ within the period T_{PWM} and the period T_{PWM} itself defines the duty cycle δ:

$$\delta = \frac{\tau}{T_{PWM}} \tag{9.1}$$

The duty cycle is representative of the valve working cycle and more specifically defines the fraction of time in which the valve is completely open within the aforementioned period. Neglecting the valve components inertia, i.e. the time required for the valve opening and closing operations, the duty cycle is directly proportional to the fuel mass flow rate fed to the combustion chamber. The duty cycle δ is defined between 0 and 1 and its regulation is possible by changing the active time τ, whereas the period T_{PWM} is a control system constant.

Solenoid valves controlled with PWM signals typically operate with impulse frequencies f_{PWM} ranging between 1 Hz and 10 kHz i.e with periods T_{PWM} ranging from 1 ms to 0,1 s. In the present case $f_{PWM} = 25$ Hz i.e. $T_{PWM} = 0{,}04$ s.

If $\delta = 0$ and $\delta = 1$ then the PWM signals are *continuous* and constant with time. The two cases are representative for the valve always on state 0 and 1 respectively. If $0 < \delta < 1$ then the valve is completely open only for a fraction of the entire period T_{PWM}. In time percentage terms it is equal to $\delta(\%)$.

The PWM signal arises from two different signals: a carrier signal and a command signal. The former, e.g. a triangular or a sawtooth signal, is also known as the chopping signal since it imposes the characteristic constant period T_{PWM} to each PWM impulse. The latter, e.g. a sinusoidal signal, is also known as the modulating signal since through its temporal law it can vary the duty cycle associated with each PWM impulse.

As shown in greater detail in figure 9.2, the train of PMW impulses is the result of a continuous comparison, made by a comparator, between the carrier and the modulating signals.

Whenever the modulating signal is greater (smaller) that the carrier signal then the comparator reaches its positive (negative) saturation voltage. This situation corresponds to an instantaneous generation in the PWM impulse train of the state 1 (state 0).

Such behaviour is due to the nature of the comparator. Comparators are open loop amplifiers with two current intensity inlet ports and one voltage outlet port. Their open loop architecture is characterized by such high gains that even a small difference in the two inlet signals can lead to (positive or negative) saturation of the outlet voltage signal. The temporal law by which such voltage signal varies between its saturation values, defines the instantaneous operations made by the control system to set the *state* of the valve moving element.

The solenoids of the fuel supply system valves are designed to operate with a potential difference comprised

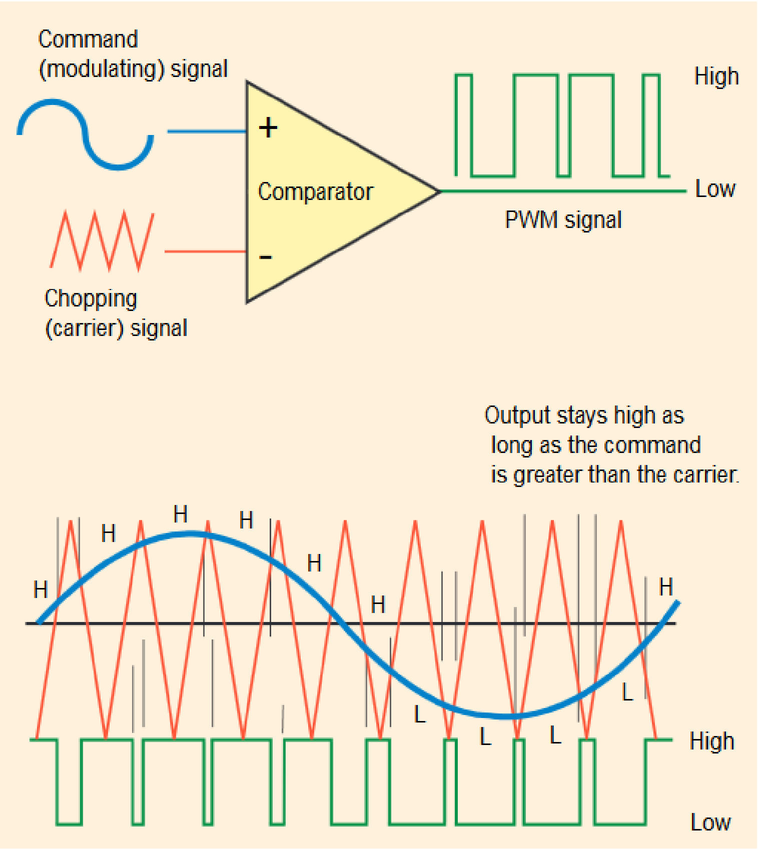


Figure 9.2: ***PWM signal genesis***

between 0 and 24 V. Such potential difference is constant with time and equal to 0 and 24 V whenever $\delta = 0$ and $\delta = 1$ respectively. If $0 < \delta < 1$ then such potential difference pulsates with time and its time-integral mean value is comprised between 0 and 24 V.

Being the valves electronically controlled with PWM signals, the MGT control logic can be understood only if reference is made, not to the valve cross sectional flow area, but to the time percent by which it remains completely open within the period T_{PWM} i.e. to the duty cycle percent value $\delta(\%)$.

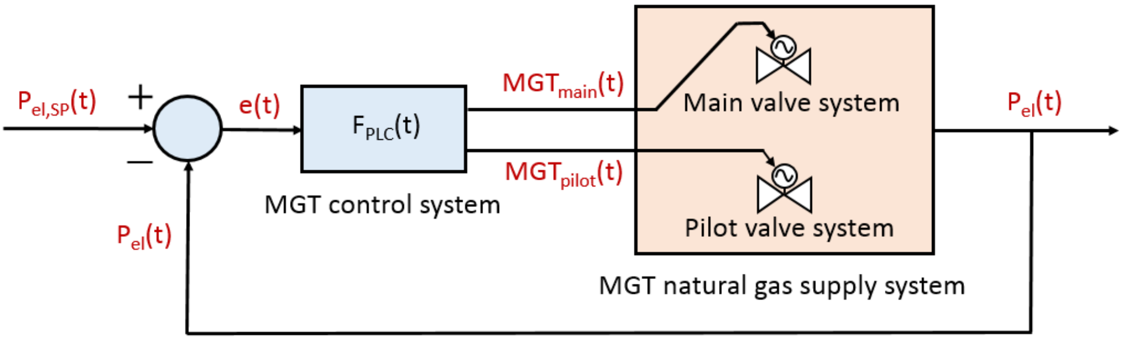


Figure 9.3: ***Original closed loop MGT control logic***

Figure 9.3 shows the original closed loop MGT control logic. The main signals entering the PLC are the instantaneous electrical power output $P_{el}(t)$ and its set point value $P_{el,SP}(t)$ i.e. the desired electrical power output. The control system summing block instantaneously compares the aforementioned signals and generates the following error function $e(t)$:

$$e(t) = P_{el,SP}(t) - P_{el}(t) \tag{9.2}$$

According to the error function value, the PLC outputs the pair of signals $[MGT_{main}(t),\ MGT_{pilot}(t)]$ so as to define a suitable control action for both the pilot and the main fuel valves. Being $F_{PLC,main}$ and $F_{PLC,pilot}$ the transfer functions that the PLC associates to the aforementioned fuel valves, the following relations hold:

$$MGT_{main}(t) = F_{PLC,main}(t)e(t) \tag{9.3}$$

$$MGT_{pilot}(t) = F_{PLC,pilot}(t)e(t) \tag{9.4}$$

The signals $MGT_{main}(t)$ and $MGT_{pilot}(t)$ exiting the PLC can vary their current intensity from 0 to 20 mA. Each signal is then converted to a PWM signal which alters the duty cycle of each fuel valve. Figure 9.4 shows the electronics in charge of such operation.

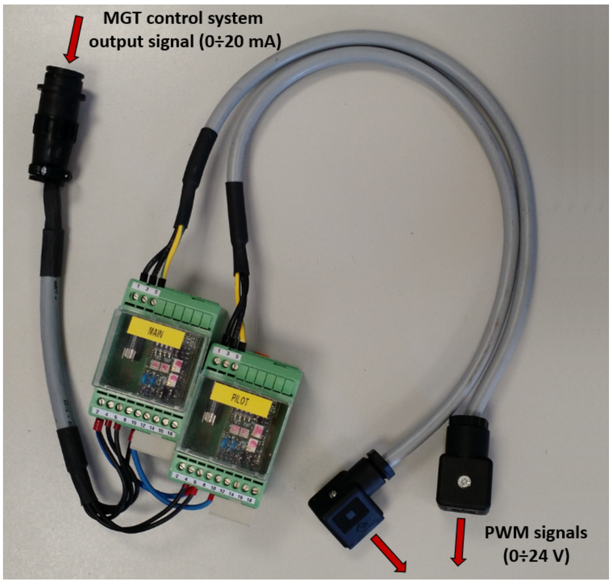


Figure 9.4: ***Electronics which converts the 0-20 mA MGT control system signal into a 0-24 V PWM signal***

Being Ω_{PWM} the function that converts the direct current (DC) signal into the PWM signal, the following relations hold:

$$\delta(\%)_{main,NG}(t) = \Omega_{PWM} MGT_{main}(t) \tag{9.5}$$

$$\delta(\%)_{pilot,NG}(t) = \Omega_{PWM} MGT_{pilot}(t) \tag{9.6}$$

where $\delta(\%)_{main,NG}(t)$ and $\delta(\%)_{pilot,NG}(t)$ are the duty cycle percent values associated with the main and pilot valves of the natural gas (NG) supply system.

The pair of signals $[\delta(\%)_{main,NG}(t),\ \delta(\%)_{pilot,NG}(t)]$ is directly associated with the pair of values $[\dot{m}_{f,main,NG}(t),\ \dot{m}_{f,pilot,NG}(t)]$ which defines the fuel mass flow rates regulated by the main and pilot valves respectively of the natural gas supply system. Therefore both the instantaneous thermochemical power input $P_{tc}(t)$ and the instantaneous electrical power output $P_{el}(t)$ can be derived. The latter quantity is scaled down from the former through the instantaneous MGT overall efficiency $\eta_{o,MGT}(t)$.

The MGT control system is designed to intervene on the pair of signals $[MGT_{main}(t),\ MGT_{pilot}(t)]$ in order to guarantee the desired electrical power output $P_{el,SP}(t)$ regardless of any external disturbances acting on the control system. In particular if the error function $e(t)$ is instantaneously positive (negative) then there is a lack (excess) in the instantaneous electrical power output with respect to its set point value. Therefore the MGT control systems reacts by increasing (decreasing) the duty cycle percent value to one or both valves i.e. the fuel mass flow rate regulated by one or both valves into the combustion chamber. In every case the MGT control system acts so as to instantaneously cancel the error function $e(t)$ value.

Tests conducted by ENEA on the original Turbec T100 P MGT have shown its control system tendency to intervene exclusively on the main valve signal $MGT_{main}(t)$ whenever the load is between 50 and 100%. Hence every time such load conditions are met, the pilot valve signal $MGT_{pilot}(t)$ is almost insensitive to load variations within such interval. Only during the transients that follow very high load variations (e.g from 100% to 20% load), significant changes in $MGT_{pilot}(t)$ have been registered. For loads lower than 50%, instead, the MGT control system intervenes on both signals even in the absence of high load variations.

Such behaviour is the consequence of the high load flexibility which characterizes current gas turbines. In fact such engines should guarantee stable operation while meeting pollutant emission regulations in the widest load interval possible.

To attain low NO_x pollutant emissions, combustion reactions must be completed at the lowest possible temperature. Therefore, since the diffusion flame regime is responsible for the highest combustion temperatures, its incidence in the overall combustion process, with respect to the premixed flame regime, should be limited as much as possible. This requires the minimization of the amount of fuel injected through the pilot fuel nozzles. The diffusion flame regime, however, is still necessary in such combustor to stabilize the premixed flame regime. Experimental tests conducted by ENEA on the original Turbec T100 P MGT showed that the amount of fuel mass flow regulated by the pilot valve is almost constant at approximately 0,4 g/s from 50 to 100% of load. As load increases from 50% to 100%, the amount of fuel sent to the pilot valve with respect to the overall fuel injected into the combustion chamber decreases from 5 to 10%.

All the above constitutes only a simplified description of the logic by which the MGT control system operates. In fact it simultaneously deals with several parameters such as rotational speed, DC-LINK supply voltage and turbine outlet temperature (TOT). Each of the above can become the main control parameter according to the MGT operating conditions (e.g. start-up procedure, transient during load variation).

For example, as shown in figure 7.9, the DC-LINK is placed between the static AC-DC converter and the static DC-AC converter. By varying the potential difference between its ends, the DC-LINK is capable to change the MGT load. In fact if the potential difference at the DC-LINK ends increases (decreases), then the load increases (decreases) and the MGT rapidly decelerates (accelerates). Tests conducted on the original Turbec T100 P have shown that the DC-LINK intervenes significantly only during transients after high load variations as well as during the start-up procedure.

Perhaps the most important physical quantity observed by the control system is the turbine outlet temperature (TOT). In fact, its value is to be kept lower than 650 °C in order to avoid any damage to the metallic surfaces of the recuperator.

9.2 Modified control logic in Turbec T100 MGT to allow for dual fuel operation

In order to integrate the dual fuel operation inside the Turbec T100 P MGT, substantial both hardware and software modifications are needed.

The dual fuel combustor ARI 100 T2 is provided with both natural gas and syngas fuel nozzles hence a tailor-made syngas (SYN) supply system needs to be added to the existing natural gas (NG) supply system.

Its integration is complex due to the absence, in the original MGT control system, of a control logic capable to manage two fuel supply systems. A direct intervention on the MGT control system would necessarily require Turbec/Ansaldo specialized staff. Excluding such possibility, due to both the high expected costs and the impossibility to acquire knowledge on the MGT behaviour, an alternative route has been taken. This route is based on the goodness of the original MGT control system and avoids direct modification of the PLC control logic.

More specifically an external conditioning system (ECS) has been installed between the PLC of the MGT and the two fuel supply systems. Such external conditioning system is basically a second PLC that has been integrated into the distributed control system (DCS) that controls the entire ZECOMIX experimental plant [69]. Such ECS is shown in figure 9.5.

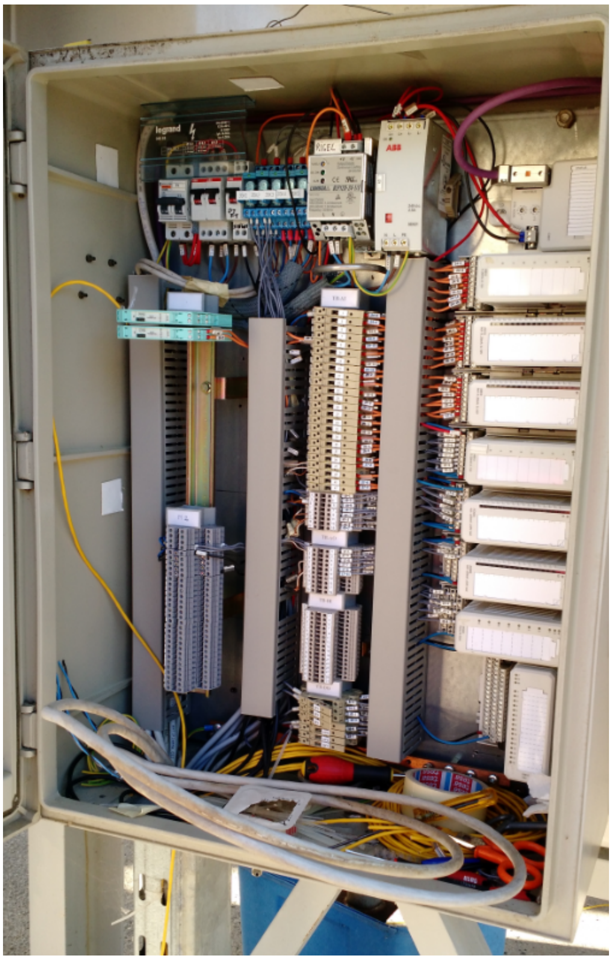


Figure 9.5: ***External conditioning system (ECS) of the ZECOMIX experimental plant***

From the MGT operator standpoint, the external conditioning system represents the effective control system through which dual fuel operation is managed, whereas, from the MGT control system standpoint, it acts equivalently as an external disturbance.
The idea is to deceive the MGT control system, which is unaware of the presence of two fuel supply systems, by commanding, through the ECS, a series of actions capable to manage both fuel supply systems. With respect to the original closed loop MGT control logic shown in figure 9.3, its modified version adopted for dual fuel operation is illustrated in figure 9.6.

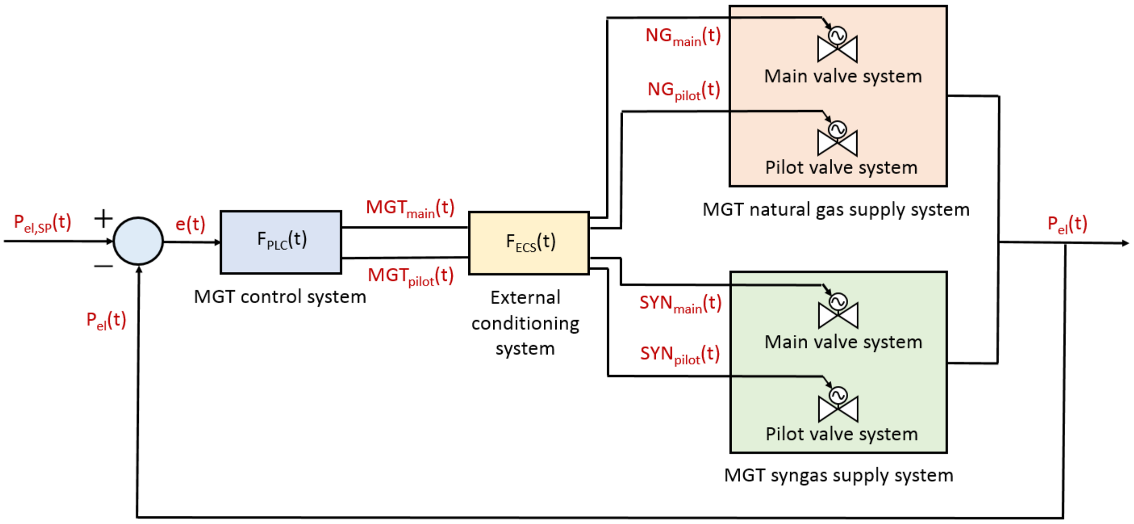


Figure 9.6: ***Modified closed loop MGT control logic for dual fuel operation***

To ease control operations, it is convenient to choose a syngas supply system with the same characteristics of the natural gas supply system as regards both the current intensity range (0 ÷ 20 mA) of the signals entering the PWM converter and the voltage range (0 ÷ 24 V) of the PWM signals. It should be noted, however, that the constructional characteristics of the two fuel supply systems are expected to be very different due to the different thermochemical nature of natural gas and syngas. For example, in normal conditions, the heating value (as well as the Wobbe index) of syngas is much lower than that of natural gas. Therefore to attain a fixed thermochemical power input, the syngas valves and nozzles need to process a higher fuel mass flow rate than the natural gas ones. Consequently, if the fuel injection velocities are to be kept similar between the two fuel supply systems, necessarily the syngas fuel system needs valves with a bigger cross sectional flow area. Therefore, with respect to the natural gas supply system, the syngas one is expected to be bulkier, heavier and *slower* due to the greater inertia of its moving components. Furthermore, since such fuel typically contains hydrogen in not negligible quantities, particular attention is required in the realization of the sealing sections.
The modified control system must manage the transition between the two fuel supply systems at a constant load. The switch procedure in course of implementation is based on the following three steps:

1. MGT start-up with natural gas supply only and thermal regulation until reaching the reference load defined for switch start-up
2. at constant electrical load, switch from natural gas to syngas by a gradual closing of the natural gas main valve and by a corresponding gradual opening of the syngas main valve

3. complete closing of the natural gas main valve and stable sustainment of the combustion reaction through a premixed regime entirely fed by syngas and a diffusion regime entirely fed by natural gas

As regards the first step of the switch procedure, the reference load for switch start-up must be chosen so as to avoid any control system intervention on the pilot valve signal. This is necessary to allow the switch procedure to be simple, stable and repeatable i.e. *controllable*. In fact the fuel injected from the pilot nozzles determines a diffusion combustion regime which is necessary to stabilize the premixed combustion occurring right downstream. Therefore sudden intervention, during the switch procedure, on the pilot valve signal would inevitably favour combustion instabilities. If such situation occurs then the entire switch procedure would be hardly controllable due to the contemporary intervention of the MGT control system on both the main valve and the pilot valve signals.

For analogous reasons the third step of the switch procedure requires to maintain active the natural gas supply on the pilot valve even after completion of the switch procedure on its main valve. It is assumed that such restriction will be removed once the stable operating dominion of the dual fuel MGT has been identified through experimental tests. At that moment, a similar switch procedure regarding the pilot valves should be developed.

As shown in figure 9.6, the external conditioning system intercepts the pair of signals $[MGT_{main}(t), MGT_{pilot}(t)]$ exiting from the MGT PLC. Each of such signals can attain a current intensity value between 0 and 20 mA. The external conditioning system transfer function, denoted as F_{ECS}, makes the following conditioning operations:

1. Copy of the pair of signals $[MGT_{main}(t), MGT_{pilot}(t)]$ exiting from the MGT PLC
2. Duplication of the copied pair of signals and deletion of the original pair of signals. In the absence of the ECS, the original pair of signals would communicate directly with the fuel valves. The ECS presence interrupts such chain of regulation and allows to generate two identical pairs of signals. One pair of signals is referred to the natural gas supply system, the other to the syngas supply system. Within each pair, one signal is associated with the main fuel valve and the other with the pilot fuel valve. Each of the above signals is defined in the interval $0 \div 20$ mA
3. Gradual attenuation of the pair of signals $[MGT_{main}(t), MGT_{pilot}(t)]$ sent towards the natural gas supply system. Being $k_{main,NG}(t)$ and $k_{pilot,NG}(t)$ the main and pilot valve signal attenuation functions, the signals exiting the ECS towards the natural gas supply system will be the following:

$$NG_{main}(t) = k_{main,NG}(t) MGT_{main}(t) \tag{9.7}$$

$$NG_{pilot}(t) = k_{pilot,NG}(t) MGT_{pilot}(t) \tag{9.8}$$

4. Gradual amplification of the pair of signals $[MGT_{main}(t), MGT_{pilot}(t)]$ directed towards the syngas supply system. Being $k_{main,SYN}(t)$ and $k_{pilot,SYN}(t)$ the main and pilot valve signal amplification functions, the signals exiting the ECS towards the syngas supply system will be the following:

$$SYN_{main}(t) = k_{main,SYN}(t) MGT_{main}(t) \tag{9.9}$$

$$SYN_{pilot}(t) = k_{pilot,SYN}(t) MGT_{pilot}(t) \tag{9.10}$$

5. Sending of the conditioned signals to the solenoids of each valve. This operation requires their conversion into PWM signals hence defines the vector of duty cycle percent values associated to all valves. Being

Ω_{PWM} such conversion function, the following relation holds:

$$\begin{aligned}&[\delta(\%)_{main,NG}(t), \delta(\%)_{pilot,NG}(t), \delta(\%)_{main,SYN}(t), \delta(\%)_{pilot,SYN}(t)]\\ &\qquad = \Omega_{PWM}[NG_{main}(t), NG_{pilot}(t), SYN_{main}(t), SYN_{pilot}(t)] \qquad (9.11)\end{aligned}$$

The vector of signals $[\delta(\%)_{main,NG}(t),\ \delta(\%)_{pilot,NG}(t),\ \delta(\%)_{main,SYN}(t),\ \delta(\%)_{pilot,SYN}(t)]$ is directly associated with the vector of values $[\dot{m}_{f,main,NG}(t),\ \dot{m}_{f,pilot,NG}(t),\ \dot{m}_{f,main,SYN}(t),\ \dot{m}_{f,pilot,SYN}(t)]$ which defines the fuel mass flow rates regulated by the main and pilot valves in both the natural gas and syngas supply systems. Therefore both the instantaneous thermochemical power input $P_{tc}(t)$ and the instantaneous electrical power output $P_{el}(t)$ can be derived. The latter quantity is scaled down from the former through the instantaneous MGT overall efficiency $\eta_{o,MGT}(t)$.

The signal attenuation/amplification functions $k_{main,NG}(t)$, $k_{pilot,NG}(t)$, $k_{main,SYN}(t)$ and $k_{pilot,SYN}(t)$ can, by definition, each attain values between 0 and 1.

The aforementioned signal conditioning operations are the most general ones that can be made with the ECS to the valve input signals. The effective signal conditioning operations that will take place during the switch, however, will be greatly simplified. Such simplifications arise from the MGT control system characteristics. In fact, as already noted, a correct choice of the reference load for the switch procedure would favour the MGT control system intervention only on the signals sent to the main valves. Therefore neither an attenuation nor an amplification is required for the signals sent to the pilot valves.

Since the MGT control system is capable to compensate to almost every external disturbance, theoretically, any temporal law is suitable for both the signal amplification and signal attenuation functions. For operational simplicity as well as to minimize gradients in those conditioning operations, ramps of equal amplitude and opposite slope have been chosen for the aforementioned functions.

Being t_0 the switch start time and t_1 the switch end time, the switch time interval Δt_{switch} is equal to:

$$\Delta t_{switch} = t_1 - t_0 \qquad (9.12)$$

Furthermore, by definition:

- at time t_0, $k_{main,NG}(t_0) = 1$ since the natural gas main valve needs no signal alteration prior to the switch start-up whereas $k_{main,SYN}(t_0) = 0$ since the syngas main valve is to be kept closed until the switch procedure is initiated

- at time t_1, $k_{main,NG}(t_1) = 0$ since the natural gas main valve is to be completely closed at the end of the switch whereas $k_{main,SYN}(t_1) = 1$ since no further signal alteration on the syngas main valve is needed once the switch procedure has been completed

If $t_0 = 0$ s, then the conditioning ramps have the following temporal dependence during the switch procedure:

$$k_{main,NG}(t) = 1 - \frac{t}{\Delta t_{switch}} = 1 - \frac{t}{t_1} \qquad (9.13)$$

$$k_{main,SYN}(t) = \frac{t}{\Delta t_{switch}} = \frac{t}{t_1} \qquad (9.14)$$

Eliminating time t from (9.13) and (9.14), the following relation holds:

$$k_{main,\text{SYN}}(t) = 1 - k_{main,\text{NG}}(t) \quad ,\forall t \tag{9.15}$$

Substituting (9.15) into (9.13) and (9.14) yields:

$$NG_{main}(t) = [1 - k_{main,\text{SYN}}(t)]MGT_{main}(t) \tag{9.16}$$

$$SYN_{main}(t) = k_{main,\text{SYN}}(t)MGT_{main}(t) \tag{9.17}$$

Equations (9.16) and (9.17) are signal conditionings equivalent to an external disturbance that the MGT control system must manage through a feedback loop to guarantee the desired electrical power output. Physically, after their conversion into PWM signals, (9.16) and (9.17) define the conditioning signals that alter the percent duty cycle values, i.e. the fuel mass flow rates, of the main valves in the natural gas and syngas supply systems.

Finally, for the entire switch duration, the signals sent to both the natural gas and syngas pilot valve are conditioned so as to keep the former unaltered from the PLC output and the latter at a value of zero. Mathematically this means that:

$$k_{pilot,\text{NG}}(t) = 1 \quad ,\forall t \tag{9.18}$$

$$k_{pilot,\text{SYN}}(t) = 0 \quad ,\forall t \tag{9.19}$$

Substituting (9.18) and (9.19) respectively into (9.8) and (9.10) yields:

$$NG_{pilot}(t) = MGT_{pilot}(t) \quad ,\forall t \tag{9.20}$$

$$SYN_{pilot}(t) = 0 \quad ,\forall t \tag{9.21}$$

As regards the duration Δt_{switch} of the switch procedure, it must be sufficiently large so as to not provoke any sudden change in the MGT operating conditions (e.g. in fuel composition, in the temperature profiles, in the local equivalence ratios nearby the primary zone) since they could lead to operational instability as regards both the combustion process as well as the control system.

Preliminary tests conducted by ENEA in the ZECOMIX experimental plant on an *in-house* modified Turbec T100 P MGT provided with two identical natural gas supply systems showed that a switch time of $\Delta t_{switch} = 5\ min = 300\ s$ should be sufficient to avoid any operational instability of the control system. Nothing can be said, *a priori*, on the incidence of Δt_{switch} on combustion stability since it is expected to be highly dependant both on the syngas supply system characteristics and on the syngas composition.

It should be noted that the introduction of the external conditioning system in the feedback control loop induces a delay in the signal processing operations.

If such delay becomes excessive, i.e. the ECS sampling frequency f_{ECS} is excessively low, then the ECS and the MGT control system operate on extremely out of sync signals. This could lead to the aforementioned operational instability which would require the intervention of the MGT control system on the pilot valve. Consequently the switch procedure loses its controllability.

The minimum ECS sampling frequency needed for operational stability has been experimentally determined by ENEA and is equal to $f_{ECS} = 200$ kHz, which equals to an ECS sampling time interval of $\Delta t_{ECS} = 5$ ms.

9.3 A more in depth analysis of the switch procedure

The following section is dedicated to a more in depth analysis of the switch procedure. First of all the load at which the switch is initiated must guarantee that the control system only intervenes on the main valve signals, whereas the signal directed towards the natural gas and syngas pilot valves must be respectively, constant and non zero, and zero.

Denoting $t = t_{-1}$ as an instant prior to switch start-up, by definition, the MGT electrical power output is already equal to the set point value and the syngas main valve is completely closed. In such conditions, the MGT control system produces the signal $MGT_{main}(t_{-1})$ of current intensity Λ_{-1} towards the natural gas main valve. If no load variation occurs, e.g. due to external disturbances or to changes in the set point, and no switch procedure is initiated, then the signal $MGT_{main}(t_{-1})$ is kept at a constant current intensity of Λ_{-1} by the MGT control system. The corresponding duty cycle percent value of the natural gas main valve is equal to $\Gamma_{main,NG,-1}$.

At time $t = t_{-1}$ the state of both main valves is defined by the following system of equations:

$$\begin{cases} MGT_{main}(t_{-1}) = \Lambda_{-1} \\ k_{main,NG}(t_{-1}) = 1 \\ k_{main,SYN}(t_{-1}) = 0 \\ NG_{main}(t_{-1}) = \Lambda_{-1} \\ SYN_{main}(t_{-1}) = 0 \\ \delta(\%)_{main,NG}(t_{-1}) = \Gamma_{main,NG,-1} \\ \delta(\%)_{main,SYN}(t_{-1}) = 0 \end{cases} \tag{9.22}$$

When the switch procedure begins, the ECS initiates syngas main valve opening and natural gas main valve closing. Therefore, when $t \in \Delta t_{switch}$, the system of equations that defines the state of both fuel main valves becomes:

$$\begin{cases} MGT_{main}(t) = \Lambda_t \\ k_{main,NG}(t) = 1 - k_{main,t} \\ k_{main,SYN}(t) = k_{main,t} \\ NG_{main}(t) = (1 - k_{main,t})\Lambda_t \\ SYN_{main}(t) = k_{main,t}\Lambda_t \\ \delta(\%)_{main,NG}(t) = \Gamma_{main,NG,t} \\ \delta(\%)_{main,SYN}(t) = \Gamma_{main,SYN,t} \end{cases} \tag{9.23}$$

where Λ_t is the current intensity, at time $t \in \Delta t_{switch}$, of the MGT control system output signal, $k_{main,t}$ is the value, at time $t \in \Delta t_{switch}$, of the signal amplification function acting on the syngas main valve, $\Gamma_{main,NG,t}$ and $\Gamma_{main,SYN,t}$ are the duty cycle percent values, at time $t \in \Delta t_{switch}$, of the natural gas and syngas main valves respectively.

Λ_t may be greater, lower or equal to Λ_{-1} due to both non linearities in the fuel supply systems and to the different types of fuels processed by the two fuel supply systems.

Lets now image to perform the switch procedure from a high heating value fuel to a low heating value fuel. In such case, in order to maintain the electrical power output constant at the set point value, the syngas main valve must process a greater mass flow rate than that required to the natural gas main valve.

For simplicity, lets now assume that the two fuel supply systems are constructionally identical and have valves with a linear characteristic.

During the switch procedure, the ECS increases the duty cycle of the syngas main valve and reduces, by the same amount, the duty cycle of the natural gas main valve. Such intervention ultimately reduces the instantaneous electrical power output with respect to its set point value. This power deficit is counteracted by the MGT control system through an increase in the signal $MGT_{main}(t)$, which now attains a current intensity equal to Λ_t. Due to the linear characteristic of the fuel valves, the $MGT_{main}(t)$ current intensity is expected to grow at a constant rate moving towards the end of the switch.

Such behaviour denotes the existence, during the switch procedure, of an overall positive drift in the signal $MGT_{main}(t)$ with respect to its value Λ_{-1} attained right prior the beginning of the switch.

With the same assumptions, a switch from a low heating value fuel to a high heating value fuel would determine an overall negative drift in the $MGT_{main}(t)$ signal. The absence of any drift phenomena, instead, is expected to occur only when both fuels have the same heating value.

At $t = t_1$ the switch procedure ends and the state of both fuel main valves is defined by the following system of equations:

$$\begin{cases} MGT_{main}(t_1) = \Lambda_{+1} \\ k_{main,\textsc{ng}}(t_1) = 0 \\ k_{main,\textsc{syn}}(t_1) = 1 \\ NG_{main}(t_1) = 0 \\ SYN_{main}(t_1) = \Lambda_{+1} \\ \delta(\%)_{main,\textsc{ng}}(t_1) = 0 \\ \delta(\%)_{main,\textsc{syn}}(t_1) = \Gamma_{main,\textsc{syn},+1} \end{cases} \tag{9.24}$$

where Λ_{+1} is the current intensity, at time $t = t_1$, of the MGT control system output signal and $\Gamma_{main,\textsc{syn},+1}$ is the duty cycle percent value of the syngas main valve at time $t = t_1$.

Unlike Λ_{-1}, which mainly depends on the load at which the switch procedure is initiated, Λ_{+1} depends also on the *sign* and intensity of the drift. In the case of an overall positive drift, Λ_{+1} will be greater than Λ_{-1}. Therefore, at constant load, a signal of greater current intensity is sent to the syngas main valve at the end of the switch than to the natural gas main valve at the beginning of the switch. The opposite occurs in case of an overall negative drift.

It should be noted that the drift established in the signal $MGT_{main}(t)$ propagates downstream the control loop, thus affecting the ECS output signals $NG_{main}(t)$ and $SYN_{main}(t)$, according to equations (9.16) and (9.17) respectively. Therefore if a positive drift occurs, instantaneously, *both* the aforementioned signals will tend to increase their current intensity with respect to their value prior to the switch. Simultaneously, however, equation (9.13) imposes that by the end of the switch, i.e. when $t = t_1$, the signal $NG_{main}(t)$ is to become zero. Therefore the MGT control system is expected to reach such condition by imposing to the signal $NG_{main}(t)$ a step-like evolution. Due to the mutual relationship expressed in equations (9.16) and (9.17), also the signal $SYN_{main}(t)$ is expected to assume a similar (albeit with an opposite slope) evolution.

Obviously the instantaneous drift sign can change during the switch procedure due to non linearities such as those related to the valve characteristics or to time-variations in one or both fuel compositions. Therefore, in the most general case, the above signals are expected to locally fluctuate while increasing or decreasing their value.

The following figures qualitatively show the current intensity of the various signals processed by the modified control system *main section* during the switch procedure.

Figure 9.7 refers to the case when both fuel supply systems are constructionally identical, their valves have linear characteristics and process fuels of the same type (case A). As already noted such conditions should not determine any instantaneous or overall drift phenomena. For representation clarity, the step-like evolutions of the signals $NG_{main}(t)$ and $SYN_{main}(t)$ are reported with a higher intensity and a much lower frequency than what is expected to occur during the real switch procedure.

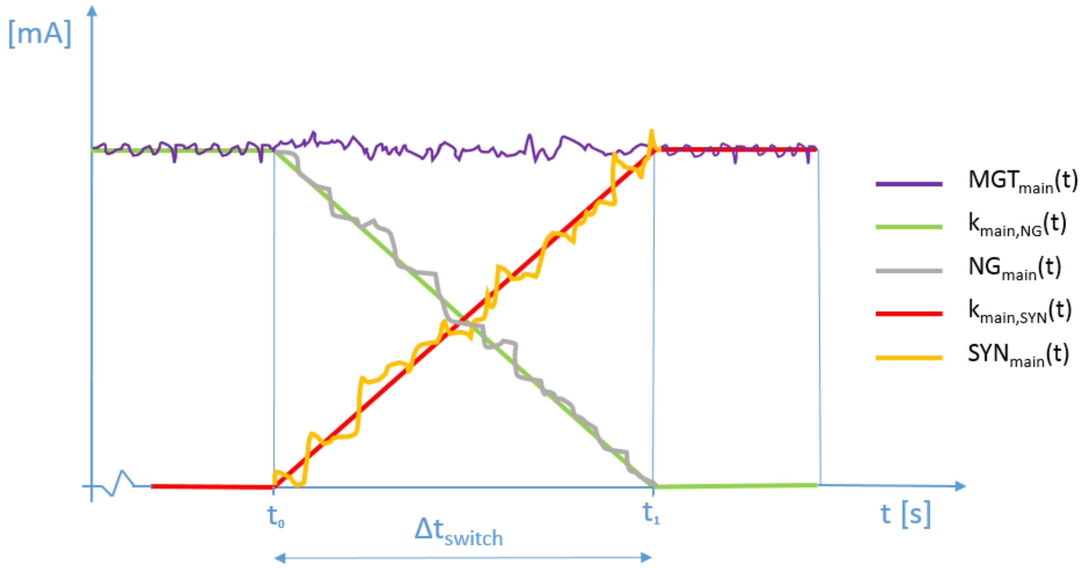


Figure 9.7: ***Qualitative behaviour of the signals processed by the modified control system main section during the switch procedure (case A)***

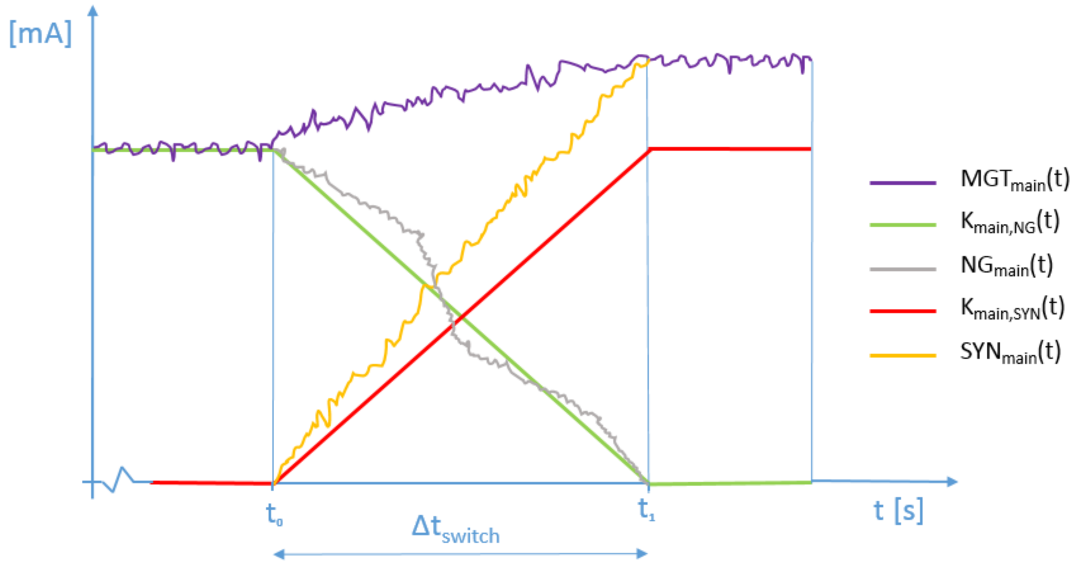


Figure 9.8: ***Qualitative behaviour of the signals processed by the modified control system main section during the switch procedure in presence of an overall positive drift (case B)***

Lets now allow each supply system to process different types of fuels and in particular lets examine the switch procedure from a high heating value fuel to a low heating value fuel (case B). Such case should produce an overall positive drift in the $MGT_{main}(t)$ signal as shown in figure 9.8.

If now the assumption of constructionally identical fuel supply systems is removed, each valve can be designed with a different cross sectional flow area. For example, lets assume that the syngas main valve is provided with a bigger cross sectional flow area than the natural gas one. In such case, during the switch procedure, the amount of syngas injected into the combustion chamber increases more rapidly than the amount of natural gas it replaces. Therefore a balance in thermochemical power input, hence in load, *can* be instantaneously achieved. If such condition is met then no drift occurs and the situation shown in figure 9.7 holds.

Nonetheless, for a specific couple of fuel supply systems, the absence of the drift can be achieved with only a specific pair of fuels. Even time-varying compositions in one or both fuels, in fact, inevitably induce a drift in the $MGT_{main}(t)$ signal.

Such example, however, shows that good design choices of the syngas fuel supply system can greatly alleviate signal drifts due to supply system or control system non linearities.

As regards the fuel supply system valves, possible non linearities may be due to the existence of dead response intervals at the extremes of their characteristics. A dead response interval defines an interval of signals for which the valve is unable to vary its state. If, for example, the signal intensity commanding a valve is too low, then the valve will remain closed until a sufficiently high signal intensity is reached. Conversely if such signal intensity is sufficiently high then the valve can reach its maximum opening state and any further increase in signal intensity produces no effect on the valve state.

These conditions occur respectively in the lower dead response interval and in the higher dead response interval.

Lets now reconsider the case of two identical fuel supply systems processing the same type of fuel but with a lower dead response interval only on the fuel supply system which is inactive at the beginning of the switch (case C).

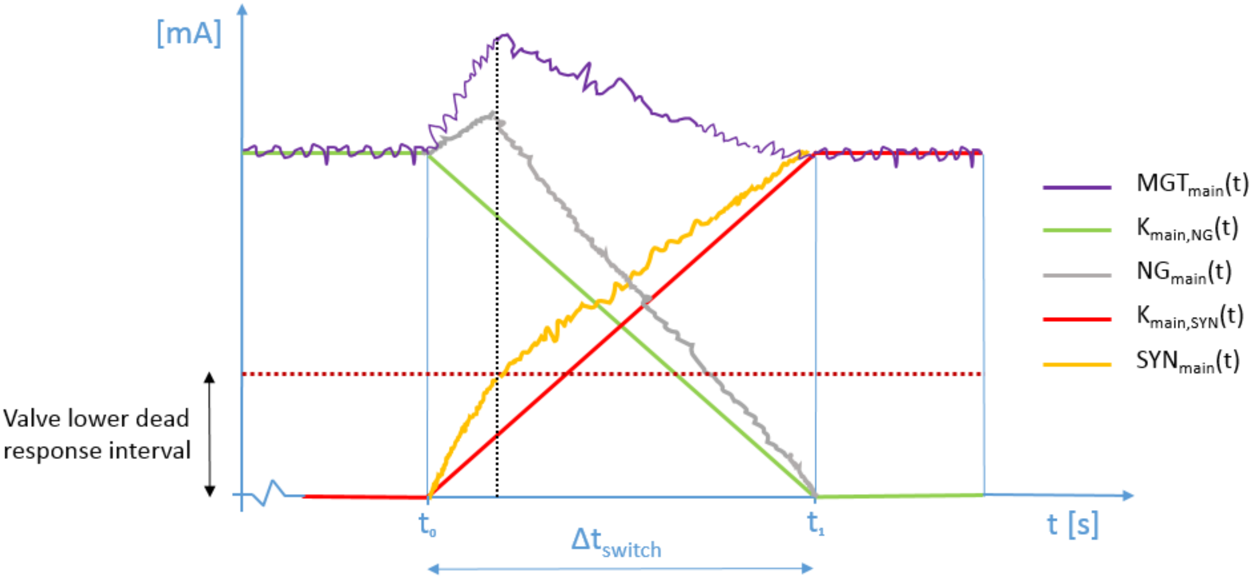


Figure 9.9: ***Qualitative behaviour of the signals processed by the modified control system main section during the switch procedure in presence of a lower dead response interval on one fuel supply system (case C)***

Figure 9.9 shows how, due to such valve non linearity, a considerable positive drift in the signal $MGT_{main}(t)$ can be produced right after the beginning of the switch procedure. In fact while one main fuel valve is closing the other is still closed and will not open until its lower dead response interval is surpassed.

The MGT control system tries to compensate to such reduction in thermochemical power input by forcing a positive drift in the $MGT_{main}(t)$ signal.

When the lower dead response interval is surpassed, the incriminated main valve finally opens and the aforementioned drift is gradually reduced until no overall drift is present at the end of the switch procedure.

Critical in determining the switch procedure success is the choice of the reference MGT load at which the switch procedure begins. A wrong choice could in fact favour system instabilities.

As already noted, a too low reference load could provoke the intervention, during the switch procedure, of the MGT control system on the pilot fuel valve signal, thus compromising the switch procedure controllability.

On the other hand, a too high reference load could lead to other system instabilities. At higher loads, in fact, the signal $MGT_{main}(t)$ current intensity is naturally *closer* to its saturation value i.e. to the maximum value which can alter the state of the valves.

Therefore even a relatively small positive drift in the signal $MGT_{main}(t)$ can lead to an over-conditioned state of the entire control system. In fact the signal $MGT_{main}(t)$ can enter the higher dead response interval of the valve it controls.

In such conditions, combustion instabilities aside, the switch procedure can either be completed with a reduction in electrical power, or can lead to MGT halt due to unsafe operations (e.g. this procedure may require an excessive TOT but the MGT control system is programmed to shut down the MGT whenever the TOT can not be contained within 660 °C).

Preliminary experimental tests have been performed by ENEA on an *in-house* modified Turbec T100 P MGT equipped with two identical natural gas supply systems. Figure 9.10 shows the interconnections of a single natural gas valve. Figure 9.11 shows the two identical natural gas supply systems installed in the Turbec T100 P MGT of the ZECOMIX experimental plant.

Figure 9.12 shows the control panel modified by ENEA to control the switch procedure in the Turbec T100 P MGT. The signal denoted as *cmd* corresponds the MGT control system output signal i.e. to $MGT_{main}(t)$.

The instantaneous amplification function $k_{main,\text{SYN}}$ is shown at the bottom right corner of figure 9.12. Its value varies from 0 to 1 in 300 s according to equation 9.14. The switch progression from one fuel supply system to the other is indicated by a green bar moving from *CH4* to *SYN*.

Such tests showed that the natural gas supply system valves are characterized by a lower dead response interval from 0% to around 31% of current intensity full scale (i.e. 20 mA). Their higher dead response interval, instead, lies from 91% to 100% of current intensity full scale.

Such switch procedure has been successfully reproduced by ENEA on an *in-house* modified Turbec T100 P MGT equipped with two identical natural gas supply systems.

Figures 9.13, 9.14 and 9.15 show the evolution of the most significant quantities during the switch procedure. The switch procedure starts at the reference electrical power of 50 kW_{el}. As clearly shown in figure 9.15, the electrical power remains constant at 50 kW_{el} for the entire duration of the switch procedure.

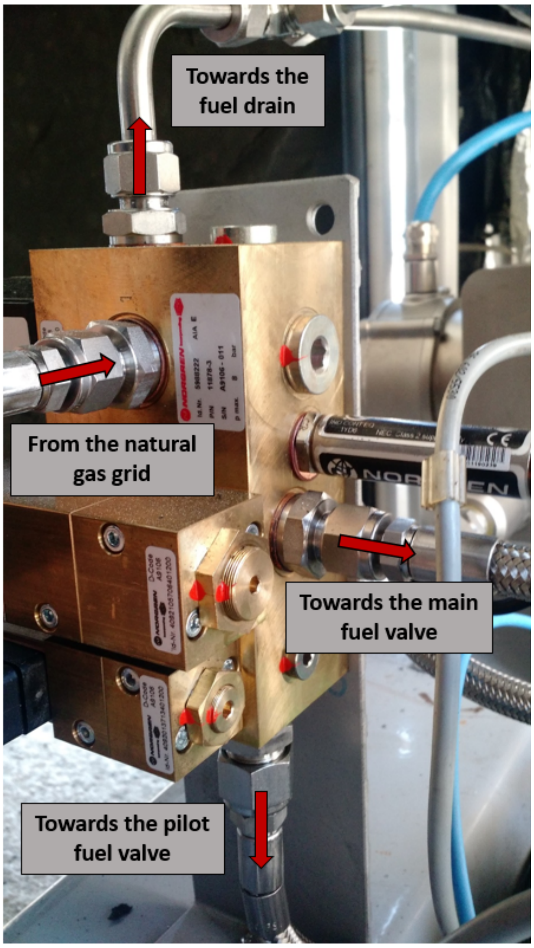


Figure 9.10: ***Interconnections of a single natural gas valve of the Turbec T100 P MGT***

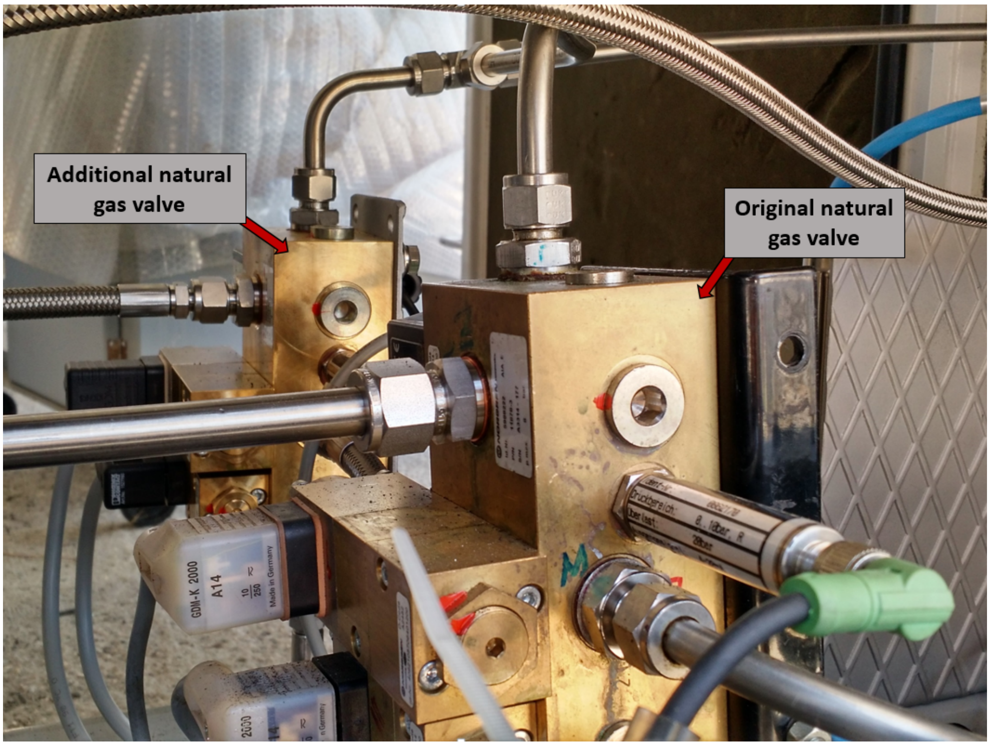


Figure 9.11: ***Installation of two identical fuel supply systems in the Turbec T100 P MGT of the ZECOMIX experimental plant***

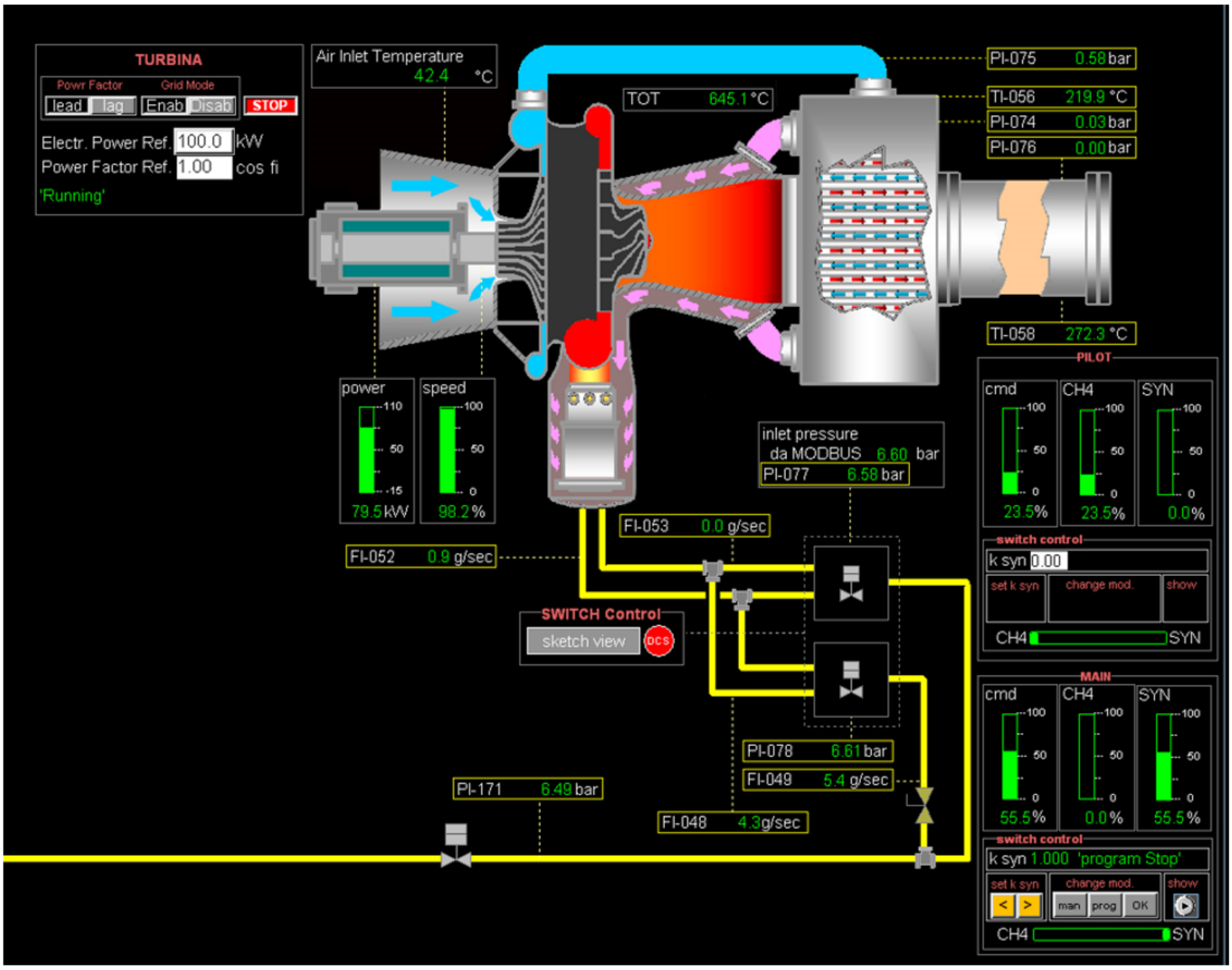
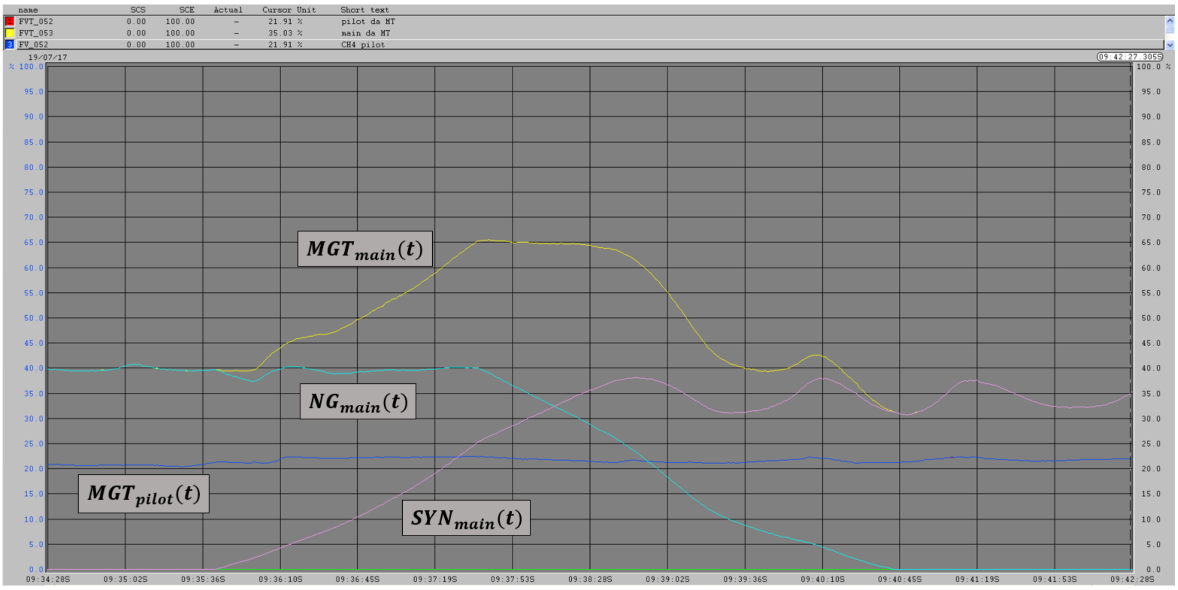
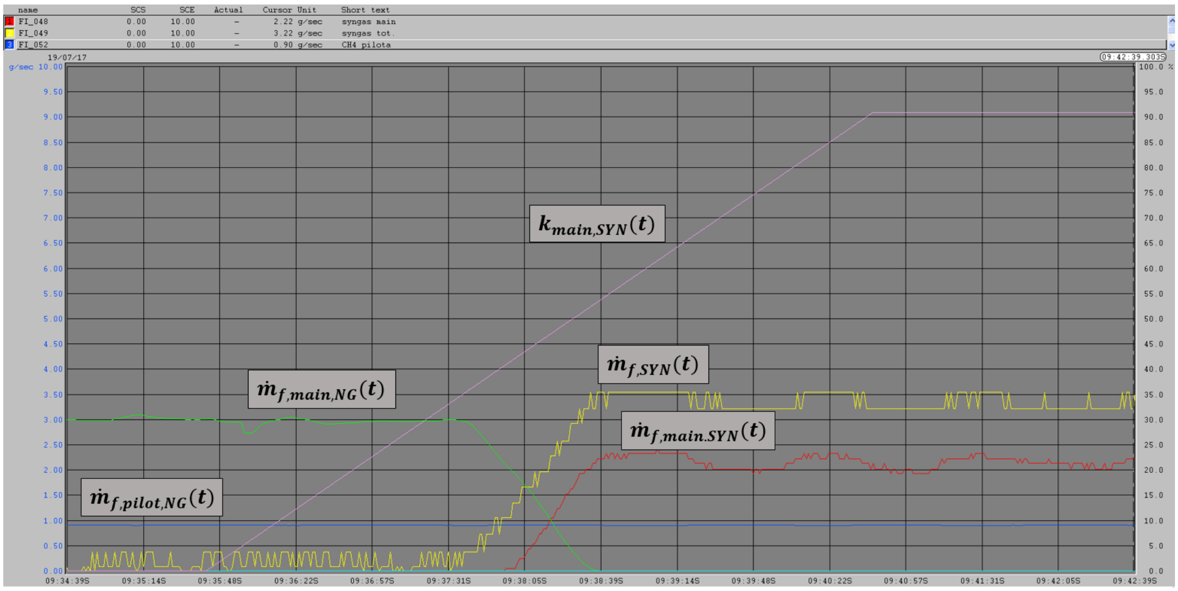


Figure 9.12: ***Control panel modified by ENEA to manage the switch procedure parameters in the Turbec T100 P MGT***



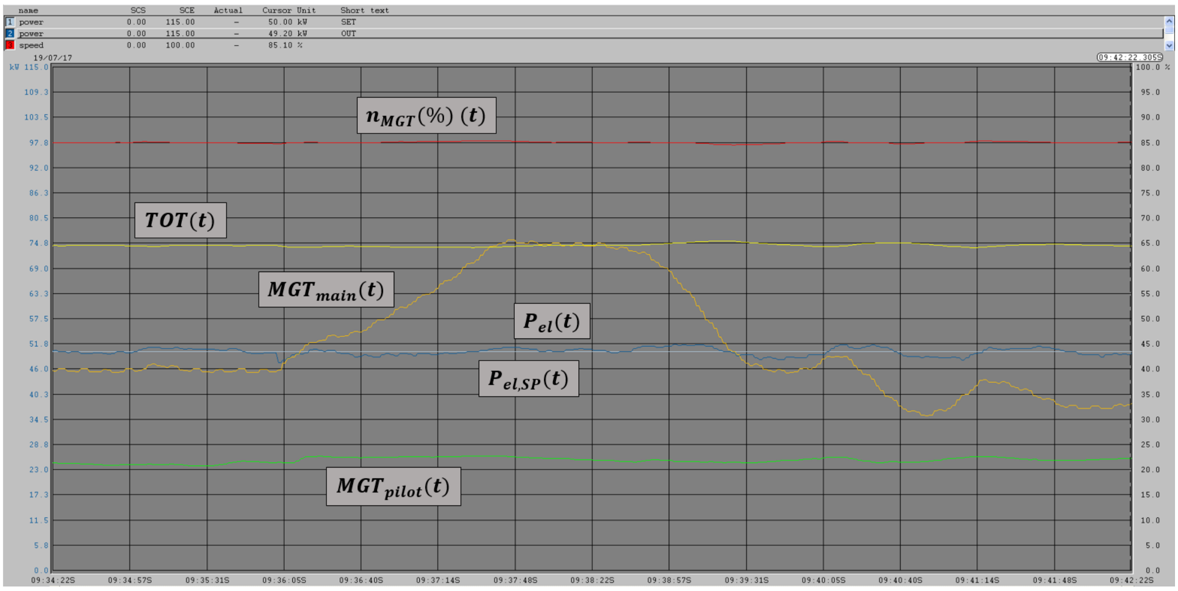
	name	SCS	SCE	Actual	Cursor	Unit	Short text
1	FVT_052	0.00	100.00	–	21.91	%	pilot da MT
2	FVT_053	0.00	100.00	–	35.03	%	main da MT
3	FV_052	0.00	100.00	–	21.91	%	CH4 pilot

Figure 9.13: ***Switch procedure at 50 kW_{el} : screen 1***



name	SCS	SCE	Actual	Cursor Unit	Short text
1 FI_048	0.00	10.00	–	2.22 g/sec	syngas main
2 FI_049	0.00	10.00	–	3.22 g/sec	syngas tot.
3 FI_052	0.00	10.00	–	0.90 g/sec	CH4 pilota

Figure 9.14: **Switch procedure at 50 kW_{el} : screen 2**



name	SCS	SCE	Actual	Cursor Unit	Short text
1 power	0.00	115.00	–	50.00 kW	SET
2 power	0.00	115.00	–	49.20 kW	OUT
3 speed	0.00	100.00	–	85.10 %	

Figure 9.15: **Switch procedure at 50 kW_{el} : screen 3**

From figures 9.13 and 9.14 an initial positive drift on the signal $MGT_{main}(t)$ is clearly visible. This is due to the lower dead response interval in the syngas main valve. The amplification function $k_{main,SYN}(t)$, in fact, needs to increase up to approximately 0,35 to surpass the lower dead response interval of the syngas main valve. Therefore only when $k_{main,SYN}(t) = 0{,}35$ the *physical* switch procedure effectively begins i.e. the natural gas main valve starts its closing procedure and the syngas main valve starts to send fuel into the combustion chamber. When $k_{main,SYN}(t) = 0{,}54$ the *physical* switch procedure effectively ends since the drift on the signal $MGT_{main}(t)$ has become practically zero. This is due to the lower dead response interval on the natural gas main valve. This ultimately leads the *physical* switch duration (approximately 1,5 min) to be considerably less than the *commanded* switch duration (exactly 5 min). It should be noted that *if* the correct reference load is chosen, as expected, the switch procedure is very stable. This is proven by the absence of significant variations in electrical power, TOT, rotational speed and natural gas mass flow rate sent to the pilot valve.