REPOWER OF NUCLEAR PLANT WITH NATURAL GAS

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Abstract. Paying attention to diversification of Brazilian energy matrix and the approach of the decommissioning of nuclear power plants in Brazil and around the world, such as Angra I nuclear power plant, planned for 2025, this paper presents a study of repowering and staggered decommissioning of a PWR (Pressurized Water Reactor) nuclear power plant from a combination of gas turbine and nuclear power plant. The proposed combined cycle "gas-nuclear", as reported in the literature, operates a gas turbine cycle connected with a nuclear power plant steam cycle (secondary loop) using a Heat Recovery Steam Generator (HRSG). After extending the life of a nuclear power plant the nuclear thermal power is gradually replaced by adding gas turbines, and then the nuclear reactor is shutdown. Energy and Exergy analysis about the combined cycle "gas - nuclear" and a standard NPP were made to compare the behavior of the arrangement. The Engineering Equation Solver (EES®) software was used for the simulations where different coupling were tested seeking the best operating conditions.

Keywords: Repower, Combined Cycle, Gas turbine, Nuclear Reactor, Decommissioning

1. INTRODUCTION

Nuclear power plants (NPP) built in the 70's and 80's are nearing the end of their useful life and will begin the decommissioning process. In Brazil, the Angra I NPP, which began operations in 1985, should start the decommissioning process in 2025, considering a useful life of 40 years. According to the CNEN 133/12 resolution, the National Nuclear Energy Commission (CNEN, 2012), Brazilian NPP may follow these decommissioning strategies: Immediate dismantling, Safestor (Deferred dismantling) and Entombment. These methods are well established in academia and are practiced in the nuclear power industry (Carajilescov et al., 2012).

Beyond the traditional forms of decommissioning, NPP may opt for repowering, or simply to postpone the operations, once proven the technical feasibility and safety. The repowering usually is an expansion of power or equipment modernization.

This work focuses on an alternative NPP repowering, based on use of exhaust gas of gas turbine to generate steam for the secondary loop in PWR (Pressurized Water Reactor) nuclear power plants. Exhaust gases heat the feedwater of secondary loop (Rankine cycle) in a Heat Recovery Steam Generator (HRSG) to generate part of steam of NPP, therefore the nuclear reactor can operate at part thermal power. It is a strategy of staggered decommissioning, wherein after extending the life of NPP, the nuclear thermal power is gradually replaced by addiction of gas turbines, then the nuclear reactor is shutdown (Fig. 1 illustrate the arrangement).

The first works of thermodynamic analysis focused on these arrangements, here called combined cycle "gas-nuclear" (CCGN), were Tsiklauri et al. (1999) and Kuznetsov et al. (1999). In the work of Tsiklauri et al. (1999) was carried out the modeling of 5 gas turbines ABB-GT24 (160 MWe) coupled to the secondary loop of Fort Calhoun NPP, a PWR with power of 484 MWe, where 50% of the feedwater was forwarded to the HRSG and the rest of the steam was generated by own nuclear reactor. This CCGN reached 47.3% of thermal efficiency, in addition to the power increment of the gas turbine, the steam turbines increased their generation, because the required extraction for the regenerative system decreased.

Kuznetsov et al. (1999) analyzed the thermodynamic model of the Russian nuclear power plant VVER-440 type, a Russian PWR, coupled to various types of gas turbines. The author also tested the configuration in which the feedwater was extracted and injected at different pressure levels. In this new arrangement the author proposes the generation of superheated steam in the HRSG to be expanded on additional turbine before to return for secondary loop. The CCGN studied presented thermal efficiency of 49.3%.

In both papers reported above, after the reactor shutdown would remain a conventional combined cycle with secondary loop of NPP. The option of staggered decommissioning enables the use of the power generation site for the "new" conventional combined cycle, which already has a connection to the electrical system.

Further to the staggered decommissioning, Tsiklauri et al. (1999) pointed out that the reduction of the nuclear thermal power increases the useful life and safety of the plant, since at low power the neutron flux in the reactor is reduced, which also reduces damage to the walls of the reactor pressure vessel.

Recent studies involving CCGN are designs of new plants built in CCGN configuration. Darwish et al. (2010) proposes an AP600 (Westinghouse®) reactor combined with Siemens gas turbine V94.3A, which achieves efficiencies higher than 50%, beyond of increase in power production in 34% when compared to separated plants. Another work,

Kasilov et al. (2015), proposed the combination of gas turbine and SVBR-100 Modular Reactor (Rosatom®), a fast neutron reactor, obtaining thermal efficiency of 45.4% in CCGN configuration.

The presented work analyzed energy and exergy behavior of CCGN, which repowering and staggered decommissioning are considered, such as Tsiklauri et al. (1999) work. However, this work used another nuclear plant model and proposed feedwater extraction for the HRSG at another point in secondary loop, the point 40 in Fig. 1 (Tsiklauri et al. studied in the point 24). The change aimed a configuration where the heat exchangers of regenerative system does not operate with less feedwater, outside of design conditions, and also does not underuse the regenerative system after the reactor shutdown. Energy analysis point out the CCGN thermal efficiency and exergy analysis point out the majors irreversibilities in CCGN.

3. THE COMBINED CYCLE *GAS-NUCLEAR*

The CCNG model was based on a typical 640 MWe PWR nuclear power plant, which is derived from thermodynamic model of Sayyaadi (2009), where only the secondary loop was detailed. The secondary loop operates with saturated steam at 6.86 MPa with high and low pressure turbine. Like most PWR NPP, the thermal efficiency of this model is 33.68%.The gas turbine model was the Siemens V94.3, 285 MW, whose exhaust gases have temperature of 577ºC. The models and calculations were performed in software Engineering Equation Solver (EES®).

The proposed CCNG is shown in Fig. 1. The feedwater extraction was carried out at point 40 (P40) after all the heat exchangers of the regenerative system. This thermal efficiency was calculated for operation with 50% of the nuclear thermal power (50% gas) and only gas (reactor shutdown), which was added 4 and 8 sets gas turbine + HRSG, respectively. The Tab. 1 shows the stream data of CCGN with 50% of the nuclear thermal power.
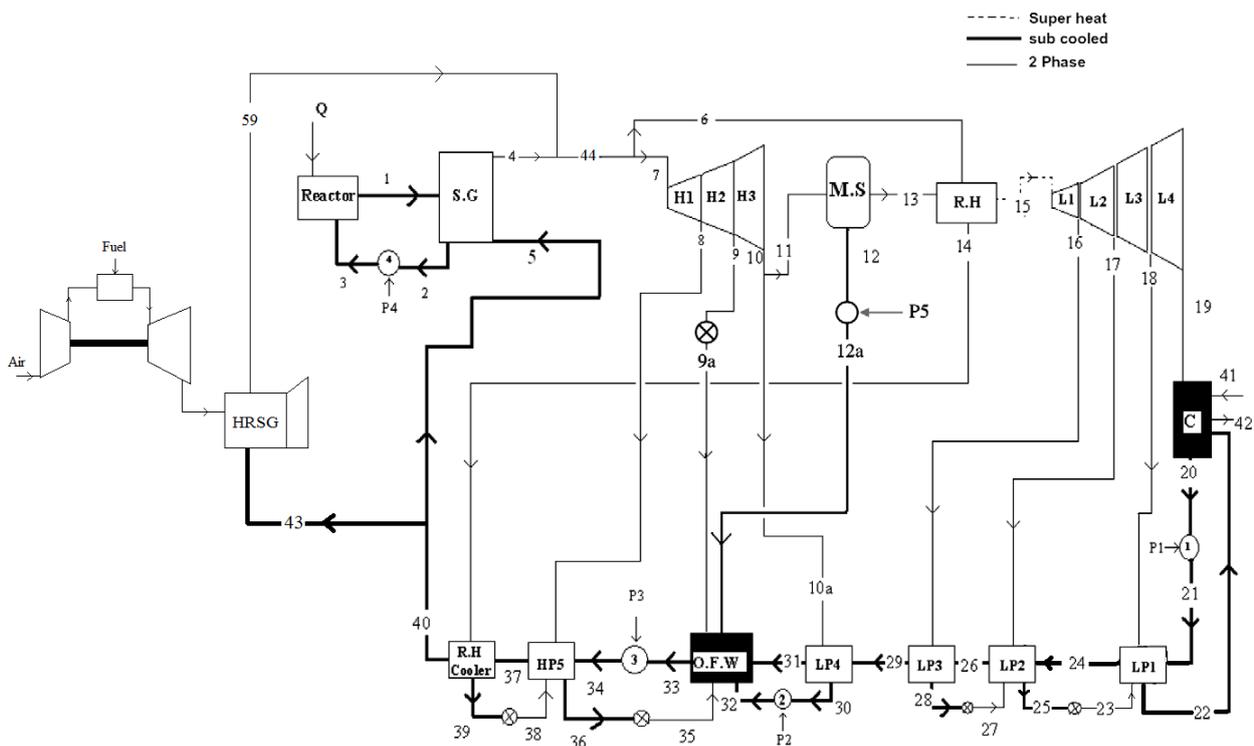

Figure 1. Diagram of proposed CCGN (P40) (adapted of Sayyaadi (2009)).

In addition to proposed cycle, the thermal efficiency of the arrangement proposed by Tsiklauri et al. (1999) was calculated. This arrangement has the feedwater extraction at point 24 (P24) of secondary loop, before the regenerative system.

3.2 Governing equations

The CCGN energy analysis was carried out by the energy balance (1st law of thermodynamics), shown in Eq. (1) (Cengel and Boles, 2013). The analysis assumed steady-state and adiabatic behavior in equipment.

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out} + \dot{W} \tag{1}$$

Table 1. Stream data for plant that is shown in Fig.1.

Stream	Flow rate (kg/s)	T (ºC)	P (kPa)	Vapor fraction	Enthalpy (kJ/kg)	Exergy (kJ/kg)
1	6899,6	326,1	15800	-	1489,79	455,6
2	6899,6	302,12	15350	-	1348,65	385,7
3	6899,6	302,33	15800	-	1349,40	386,4
4	551,601	284,55	6865	0,9978	2770,21	1040
5	551,601	233	6865	-	1004,78	225,4
6	116,555	284,55	6865	0,9978	2770,21	1040
7	986,647	284,55	6865	0,9978	2770,21	1040
8	101,76	226,08	2600	0,9039	2626,68	875,5
9	39,487	198,33	1500	0,8755	2549,16	785,8
9a	39,487	180,48	1013	0,8862	2549,16	742
10	845,4	168,92	771	0,8503	2460,15	681,7
10a	60,815	168,92	771	0,8503	2460,15	681,7
11	784,586	168,92	771	0,8503	2460,15	681,7
12	110,75	168,92	771	0	714,55	113,4
12a	110,75	168,96	1013	-	714,87	113,7
13	673,836	168,92	771	0,9901	2747,05	775,1
14	116,555	284,55	6865	0,3035	1719,39	551,4
15	673,836	240	771	Superheated	2928,81	842,1
16	34,628	121,67	192,8	Superheated	2710,34	582,1
17	18,24	104,88	120,3	0,9831	2645,36	504,3
18	28,755	75,93	40,09	0,944	2506,35	335,6
19	592,213	40,3	7,5	0,895	2321,30	106,6
20	673,836	40,3	7,5	0	168,76	1,494
21	673,836	40,37	1013	-	169,95	2,516
22	81,623	40,3	7,5	0,062	317,87	8,772
23	52,868	75,93	40,09	0,05254	439,66	34,07
24	673,836	65	1013	-	272,90	11,22
25	52,868	104,88	120,3	0	439,66	38,23
26	673,836	80	1013	-	335,70	19,84
27	34,628	104,88	120,3	0,02683	499,85	50,95
28	34,628	119,08	192,8	0	499,85	51,88
29	673,836	107	1013	-	449,29	41,03
30	60,815	168,92	771	0	714,55	113,4
31	673,836	144	1013	-	606,83	80,67
32	60,815	168,96	1013	-	714,87	113,7
33	1103,202	180,48	1013	0	765,36	130,6
34	1103,202	181,57	6865	-	773,13	137,6
35	218,315	180,48	1013	0,1025	971,72	201,3
36	218,315	226,08	2600	0	971,72	208,9
37	1103,202	222,5	6865	-	956,24	205,8
38	116,555	226,08	2600	0,1575	1260,01	325
39	116,555	284,55	6865	0	1260,01	337,6
40	1103,202	233	6865	-	1004,78	225,4
41	30765,71	25	101,3	-	104,84	0
42	30765,71	35	101,3	-	146,67	0,6862
43	551,601	233	6865	-	1004,78	225,4
44	1103,202	284,55	6865	0,9978	2770,21	1040
59	551,601	284,55	6865	0,9978	2770,21	1040

The equipment exergy analysis was performed using the exergy balance (2nd law of thermodynamics), according to Eq. (2), where the specific exergy is assumed as only physical exergy of the stream, ψ, Eq. (3), and E_D is the exergy destroyed (Irreversibility).

$$\sum \dot{Q}\left(1 - \frac{T_0}{T}\right) + \sum \dot{m}_{in}\psi_{in} - \sum \dot{m}_{out}\psi_{out} - \dot{W} = \dot{E}_D \qquad (2)$$

$$\psi = (h - h_0) - T_0(s - s_0) \tag{3}$$

The fuel exergy adopted in the gas turbine (CH4) was 831,650 kJ / kmolCH4, as Bejan et al. (1996). The exergy balance on nuclear reactor considered the input heat as fuel exergy, the considerations details can be viewed at Durmayaz and Yavuz (2001). The dead state parameters used were $T_0 = 25\ °C$ and $P_0 = 101.3\ kPa$. The isentropic efficiency in the pumps and steam turbines were 80% and 85%, respectively.

4. RESULT AND DISCUSSION

Energy efficiency and parameters of the CCGN proposed are shown in Tab. 2, where the columns 3 and 4 correspond to the feedwater extraction at point 40 (P40) and column 5 corresponds to the feedwater extraction at point 24 (P24), proposed in the Tsiklauri et al. (1999).

Table 2. Parameter and thermal efficiency of plants.

Description	Nuclear Plant	CCGN-50% gas (P40 config.)	CCGN -100% gas (P40 config.)	CCGN-50% gas (P24 config.)
Output power, MW	652,6	1720	2789,5	1819,9
Reactor thermal power, MW	1937,3	968,7	-	968,7
Gas turbine output power, MW	-	1064,5	2128,8	1064,5
Thermal efficiency, %	33,7	46,6	51,1	49,3

As seen in Tab. 2, the thermal efficiency found on CCGN models are close to those reported in the literature, which confirms the validity of the developed model.

Note that the CCGN efficiency with feedwater extraction at point 40 (P40), operating at 50% gas, was smaller than the feedwater extraction at point 24 (P24). This is due to the decreased load on the regenerative system, because less mass of feedwater flows in the regenerative system with the P24 configuration. Consequently the steam turbine extractions are smaller, resulting in more work. However, the P24 configuration would result in underutilization of heat exchangers of the regenerative system and also the operation outside of design conditions in case of gradual reduction of nuclear power for decommissioning. The P40 configuration ensures full operation of the regenerative system and still maintains high thermal efficiency levels (46,6%).

4.1 Exergy analysis

The exergy analysis mapped the irreversibilities (exergy destroyed) in CCGN equipment and in the convention NPP, the results are shown in Tab.3.

Table 3. Irreversibilities for equipment of CCGN (P40) and Nuclear Power plant.

Equipment	CCGN (P40)		Nuclear Power Plant	
	Irreversibility (MW)	Irreversibility (%)	Irreversibility (MW)	Irreversibility (%)
Combustion Chamber (GT)	847,1	45,6	-	-
Reactor	491,5	26,4	983	77,9
Gas turbine	113	6,1	-	-
HRSG	100	5,4	-	-
Turbine LP	80,6	4,3	80,5	6,4
Compressor (GT)	60,4	3,2	-	-
Turbine HP	44,7	2,4	45,1	3,6
Condenser	41,7	2,2	41,6	3,3
Steam Generator	32,3	1,7	64,6	5,1
Others (pumps and etc.)	47,7	2,7	45,7	3,7
Total	1859	100	1260,5	100

The results of the exergy analysis show that with the addition of gas turbines and HRSG the reactor is no longer a major source of irreversibility, with the combustion chamber the most responsible (45,6%). It was not found others results in the literature for comparing the irreversibility analysis of CCGN, however the analysis performed at the conventional NPP was compatible with the Durmayaz and Yavuz (2001) work, which the irreversibility percentage in the Reactor, Steam generator and Steam turbine LP were 79.7%, 4.96% and 5.41%, respectively, which confirms the validation of the model.

5. CONCLUSION

The proposed combined cycle gas-nuclear (CCGN) with feedwater extraction at point 40 showed a high efficiency, of 46.6%, operating with gas 50%. The arrangement ensures the operation of the regenerative system in their design conditions. Thus it can be seen as a repowering and staggered decommissioning alternative for "aging" nuclear power plants, improving the safety and useful life of the plants.

Note that the CCGN option for staggered decommissioning enables the use of power generation site for the future conventional combined cycle station, which is already connected to the grid, and also offers other types of infrastructure.

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